Interaction of cloud microphysics with other physical processes

: Based on the work with WSM scheme

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List of presentation

Overview of the WRF Single-Moment Microphysics

Importance of cloud ice sedimentation

Sedimentation versus microphysics

Cloudiness versus microphysics

Microphysics in regional and global models

WSMMP: WRF-Single Moment-Microphysics

Major modifications suggested by Hong et al. (2004)

	(Rutledge and Hobbs, 1983, NCEP3, D89)	**(Hong et al, 2004)**
Number concentration of cloud ice	$N_I(m^{-3}) = 10^{-2}\exp[0.6(T_0 - T)]$	$N_I = c(\rho q_I)^d$
Ice nuclei number	$N_I(m^{-3}) = 10^{-2}\exp[0.6(T_0 - T)]$	$N_{I0} = 10^3\exp[0.1(T_0 - T)]$
Intercept parameter for snow	$N_{0S} = 2\times10^7\ \mathrm{m}^{-4}$	$N_{0S}(m^{-4}) = 2\times10^6\exp\{0.12(T_0 - T)\}$

Problematic behavior of Fletcher function :

- completely removes supersaturation below -42.5C and does not above -38.5

- autoconversion from ice to snow is efficient at warmer than -27C, but not colder than -32 C.

➔ production terms are temperature dependent ➔ distributions of qi and qs are highly have little freedom in vertical

Ice crystal property

(Mass, Diameter, Mixing ratio, Ice number)

$V_I(ms^{-1}) = 3.29(\rho q_I)^{0.16}$: **Heymsfield and Donner(1990)** **(HD1990)**

$V_I = xD^y, m = \alpha D^\beta$: **Heymsfield and Iaquinta (2000)** **(HI2000)**

$mN_i = \rho q_i$

$N_i = c(\rho q_i)^d$

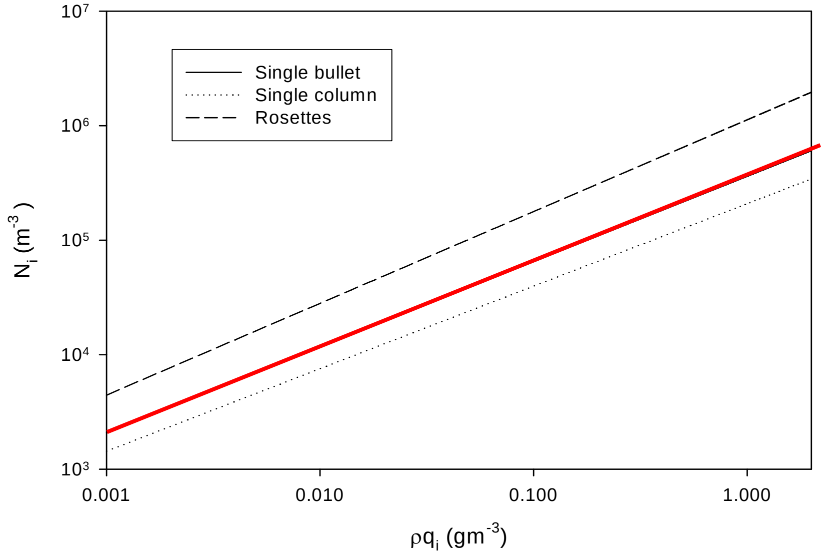
$$V_I(ms^{-1}) = 1.49\times10^4 D^{1.31},$$

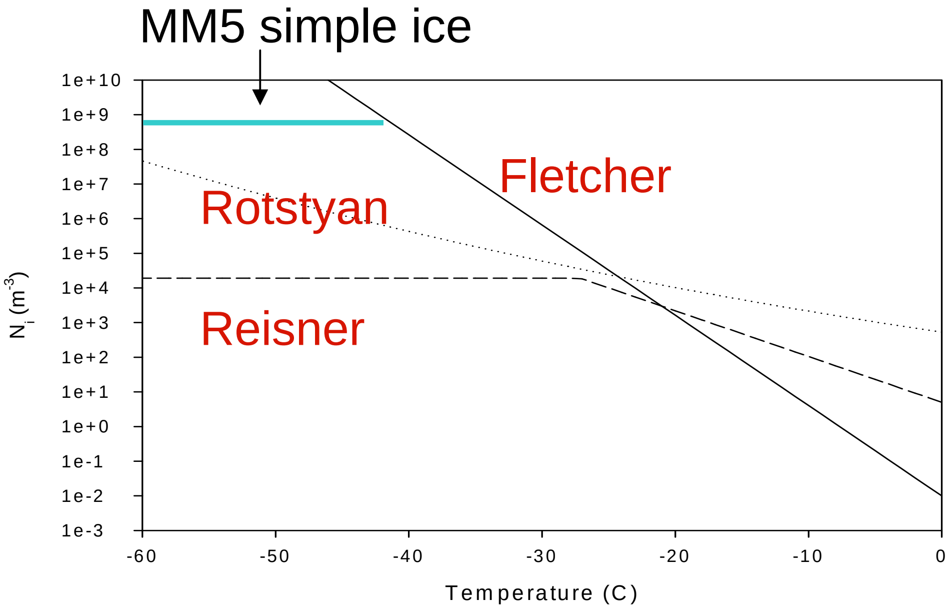
$$D(m) = 11.9m^{0.5}$$

$$N_I(m^{-3}) = 5.38\times10^7(\rho q_i)^{0.75}$$

$$\rho q_I(kgm^{-3}) = 4.92\times10^{-11} N_I^{1.33}$$

Ice number concentration (Ni)





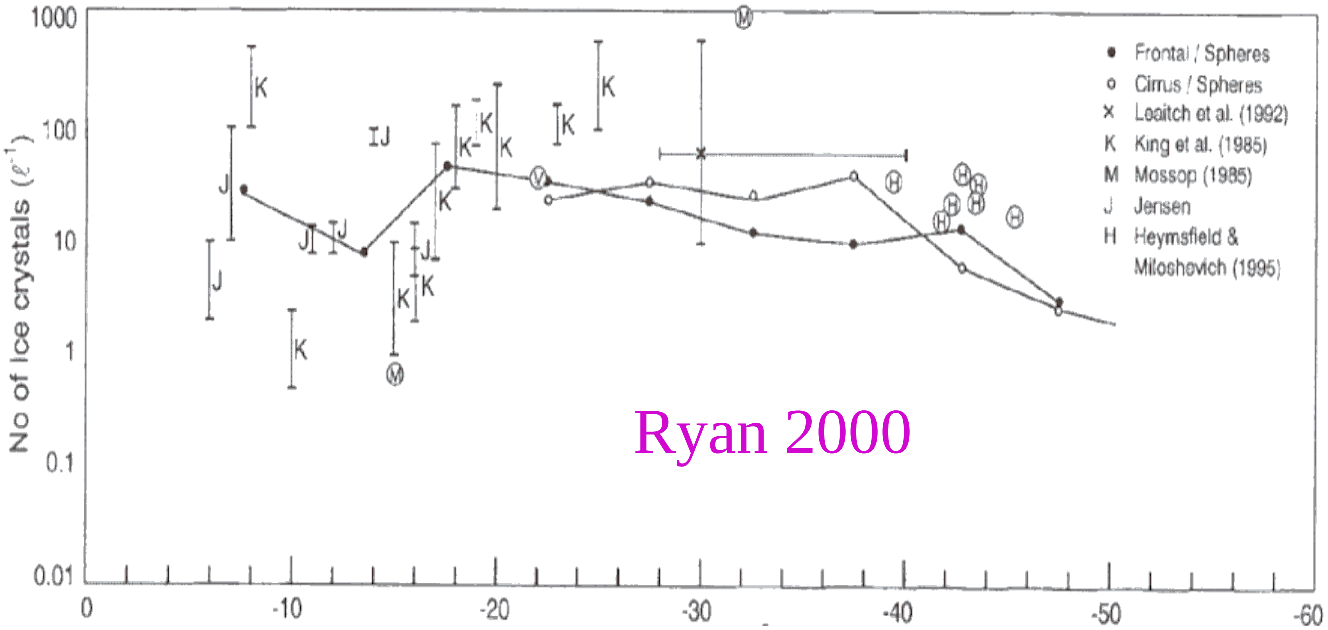
$$N_I(m^{-3}) = 5.38\times10^7(\rho q_I)^{0.75}$$:

HDC2004

$$N_I(m^{-3}) = 10^{-2}\exp[0.6(T_0 - T)]$$:

Fletcher

Observed Ni

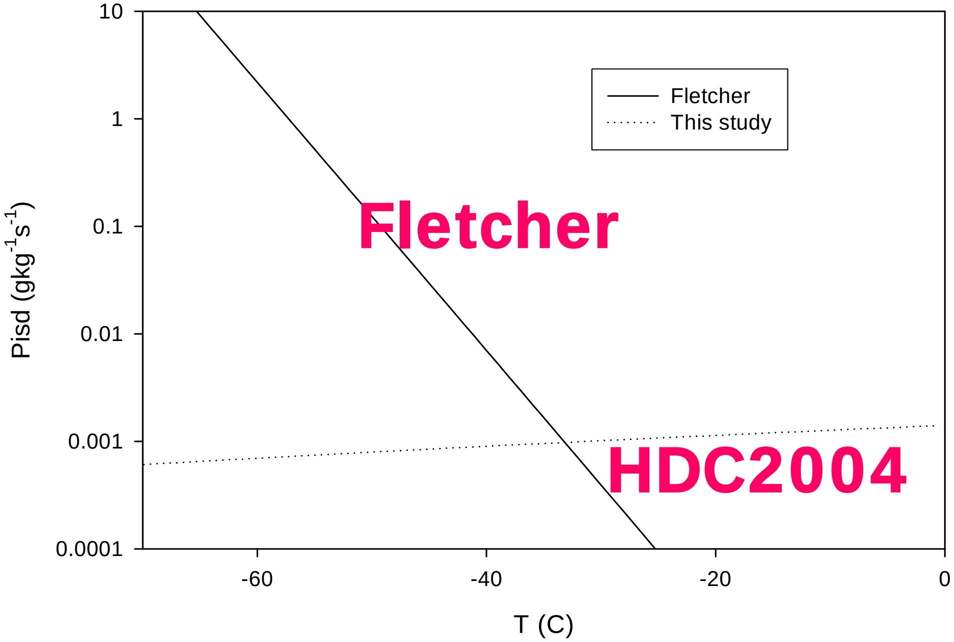


Ryan 2000

Little temperature dependency of Ni

Vapor deposition of a small ice crystal (Pidep):

$$Pidep = \frac{4\bar{D}_I(S_I-1)N_I}{A_I+B_I} = \frac{4\bar{D}_{Icon}(S_I-1)(\rho q_I N_I)^{0.5}}{A_I+B_I}$$



Even if the same formula, the actual behavior of production terms in the WSMMPs are quite different

Ice deposition should be more active at warmer temperature in nature

Hong et al. 2004

WSMMP (WRF-Single-Moment- MicroPhysics)

Hong, Dudhia and Chen (2004)

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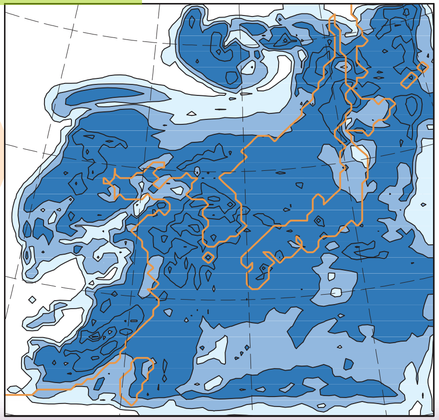
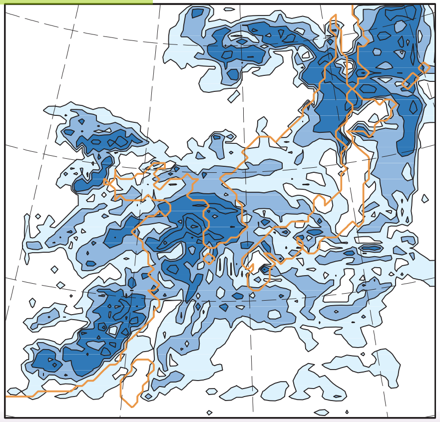
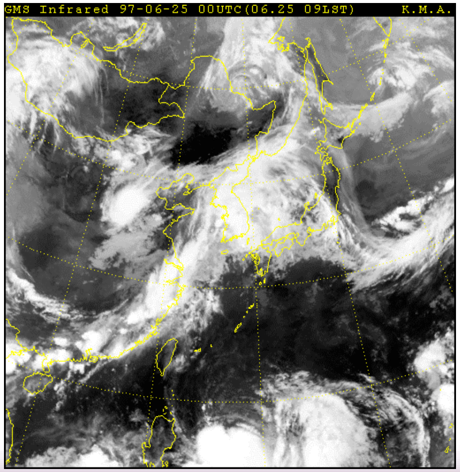
23 –25 June 1997
Heavy Rainfall Case
(Vertically integrated cloud ice)

old

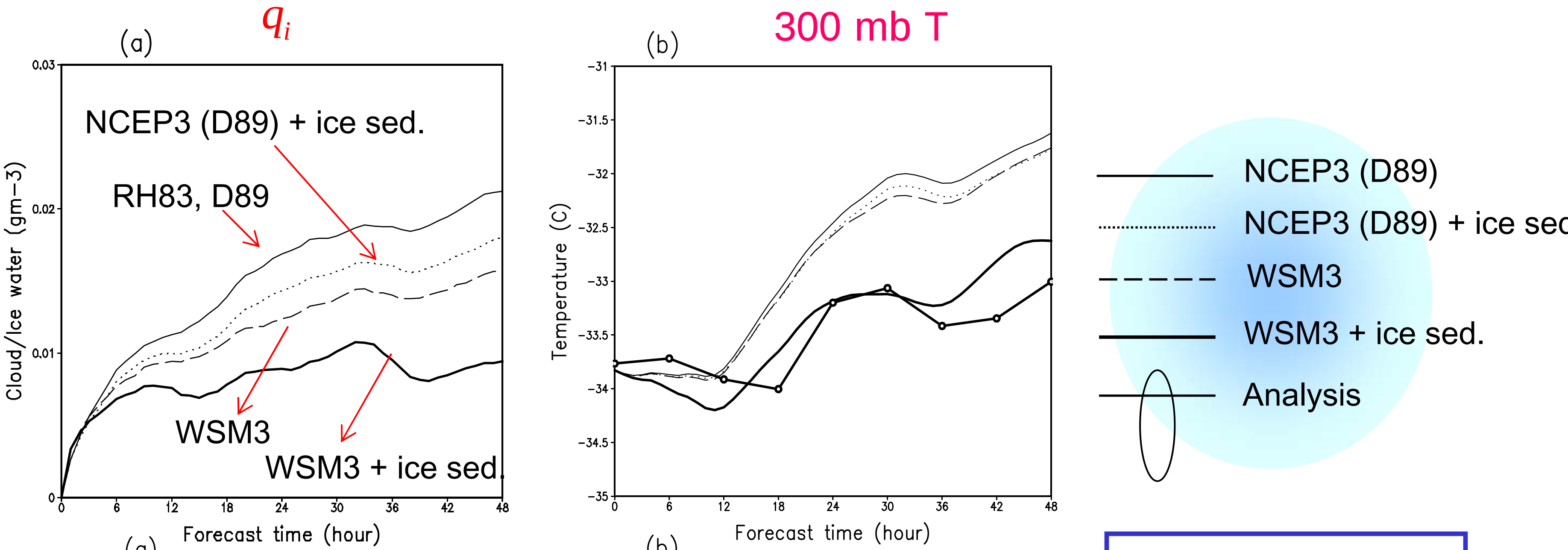


new

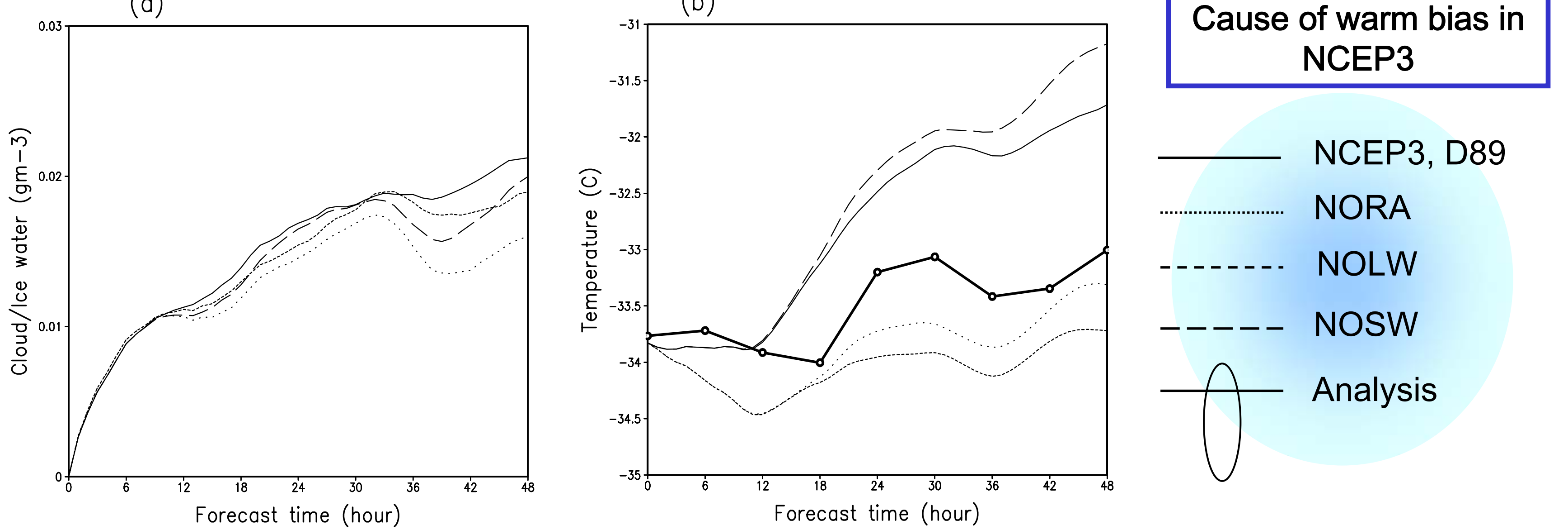




Microphysics – radiation interaction

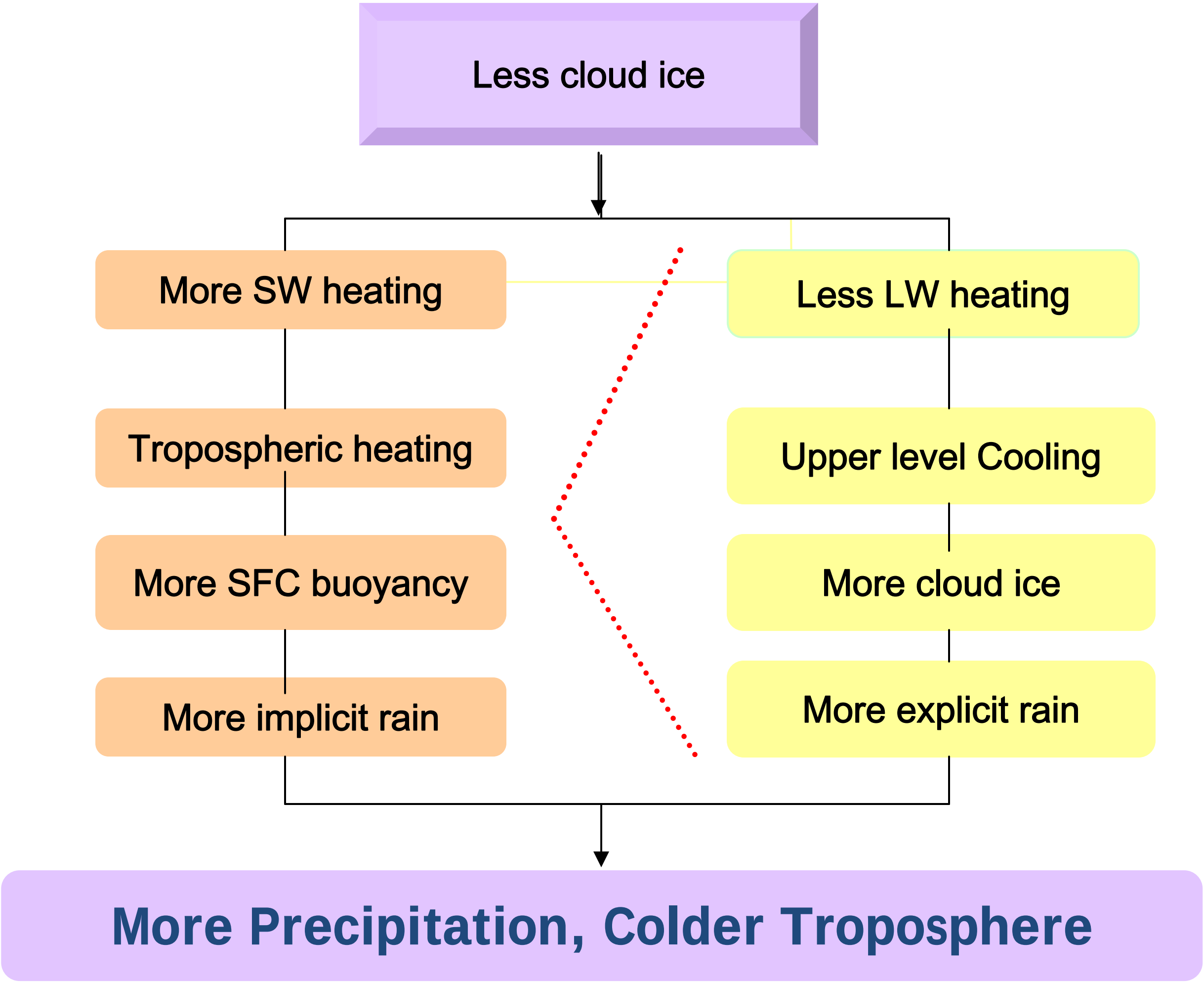


Cause of warm bias in NCEP3



Ice cloud - radiation feedback :

(HDC2004)



Less cloud ice

More SW heating

Tropospheric heating

More SFC buoyancy

More implicit rain

Less LW heating

Upper level Cooling

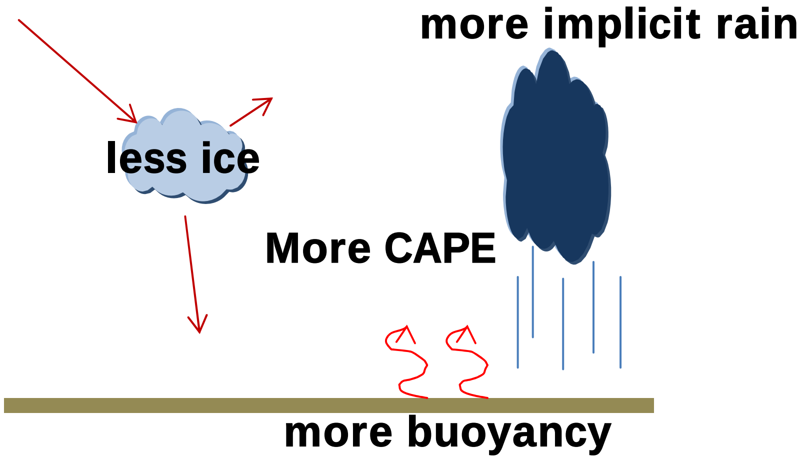
More cloud ice

More explicit rain

More Precipitation, Colder Troposphere

cloud - radiation feedback (HDC2004)

Shortwave radiation



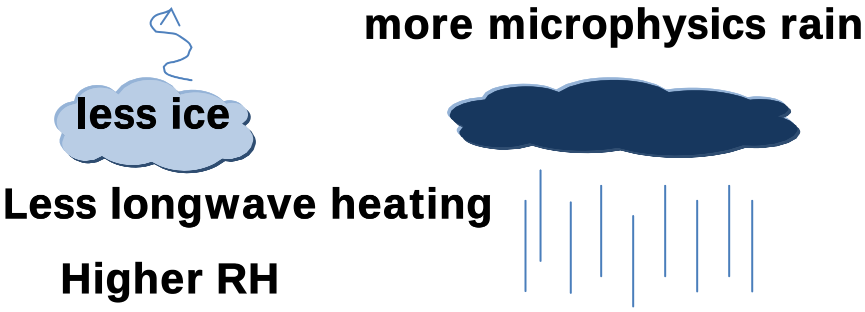
more implicit rain

less ice

More CAPE

more buoyancy

Longwave radiation



less ice

more microphysics rain

Less longwave heating

Higher RH

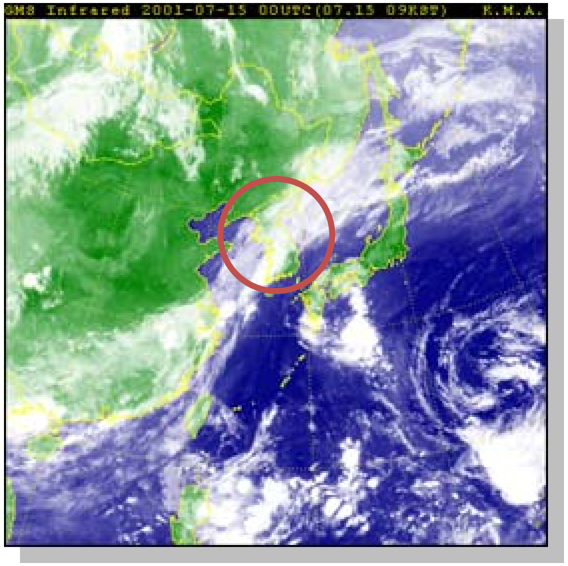
Revised microphysics, together with the inclusion of ice sedimentation, improve the simulation of precipitation and large-scale features through ice-cloud radiation feedback

Ice microphysics versus ice sedimentation

- Lim and Hong (2005, J. Geophys. Res.)

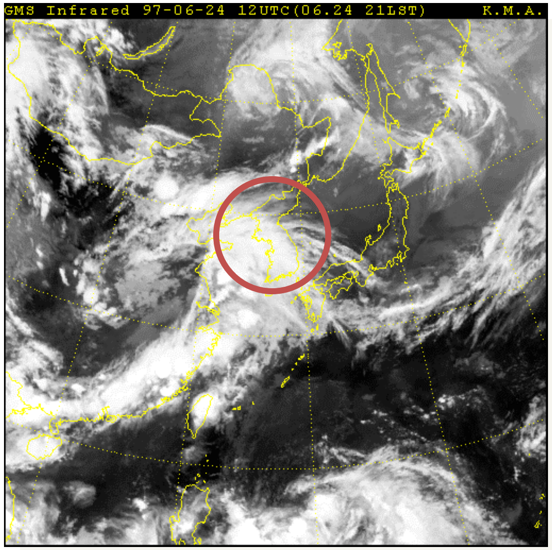
MM5 Results – case dependency

Case1



Banded type local convection
➔ Microphysics is important

Case2

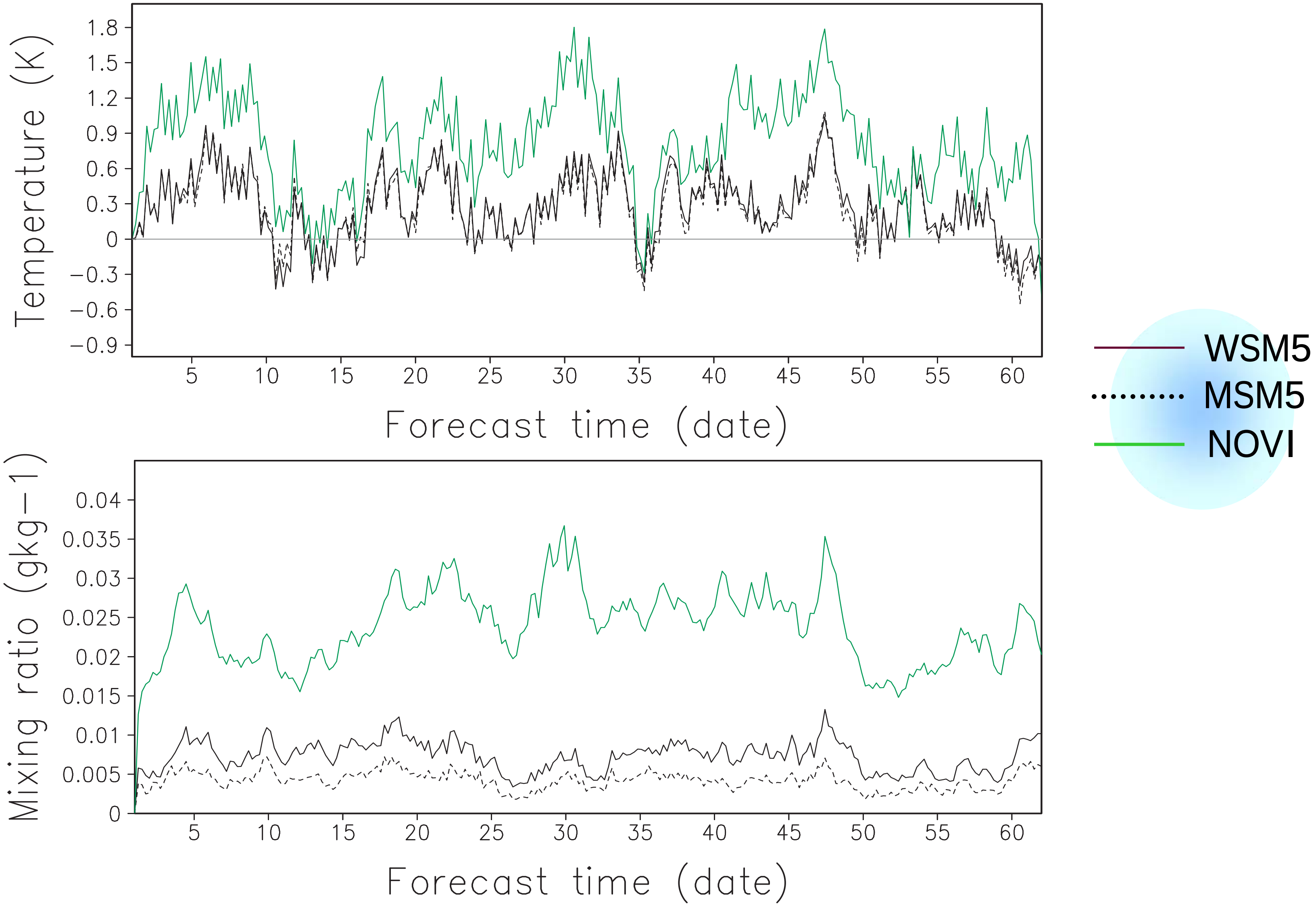


Frontal type heavy rainfall
➔ Ice sedimentation is important

MM5 Regional Climate Run

T bias

Cloud ice



Remarks on cloud ice sedimentation

Importance of microphysics is case-dependent

Sedimentation of cloud ice is important in long-term integration

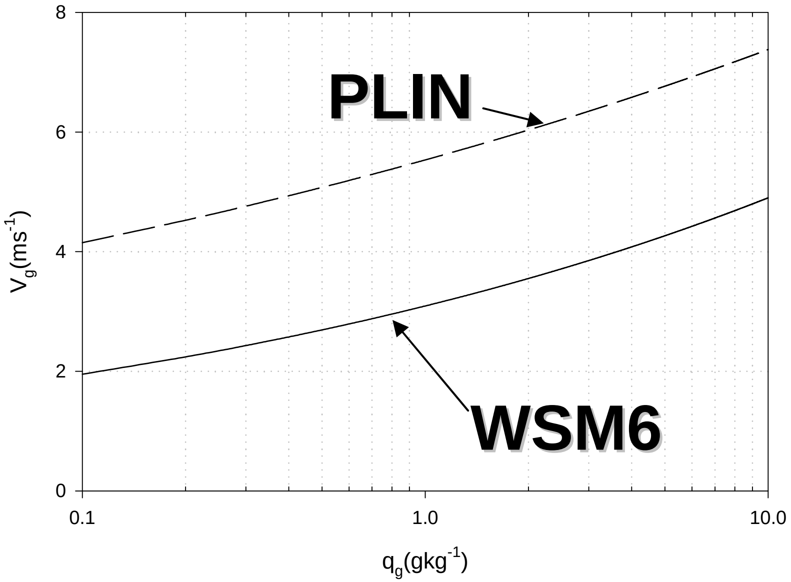
Effect of sedimentation velocity and WSMMPs – what is the major source for the different behaviors between the PLIN and WSM6 schemes ?

Hong, Lim, Kim, Lim, and Dudhia

(2008, J. Appl. Meteor. and Clim.)

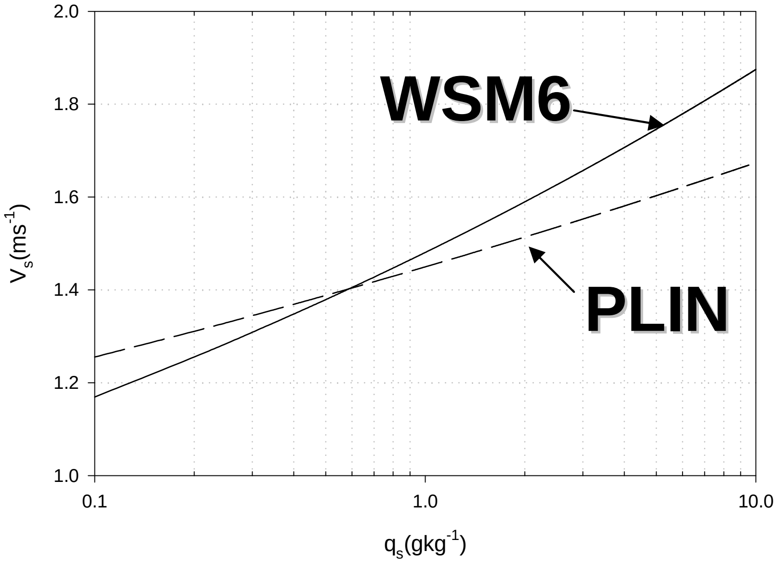
Different terminal velocity

Vg (t=0°C)



Mass weighted terminal velocity of graupel

Vs (t=0°C)



Mass weighted terminal velocity of snow

Hong et al. (2008)

WSM6 : WSM6 scheme

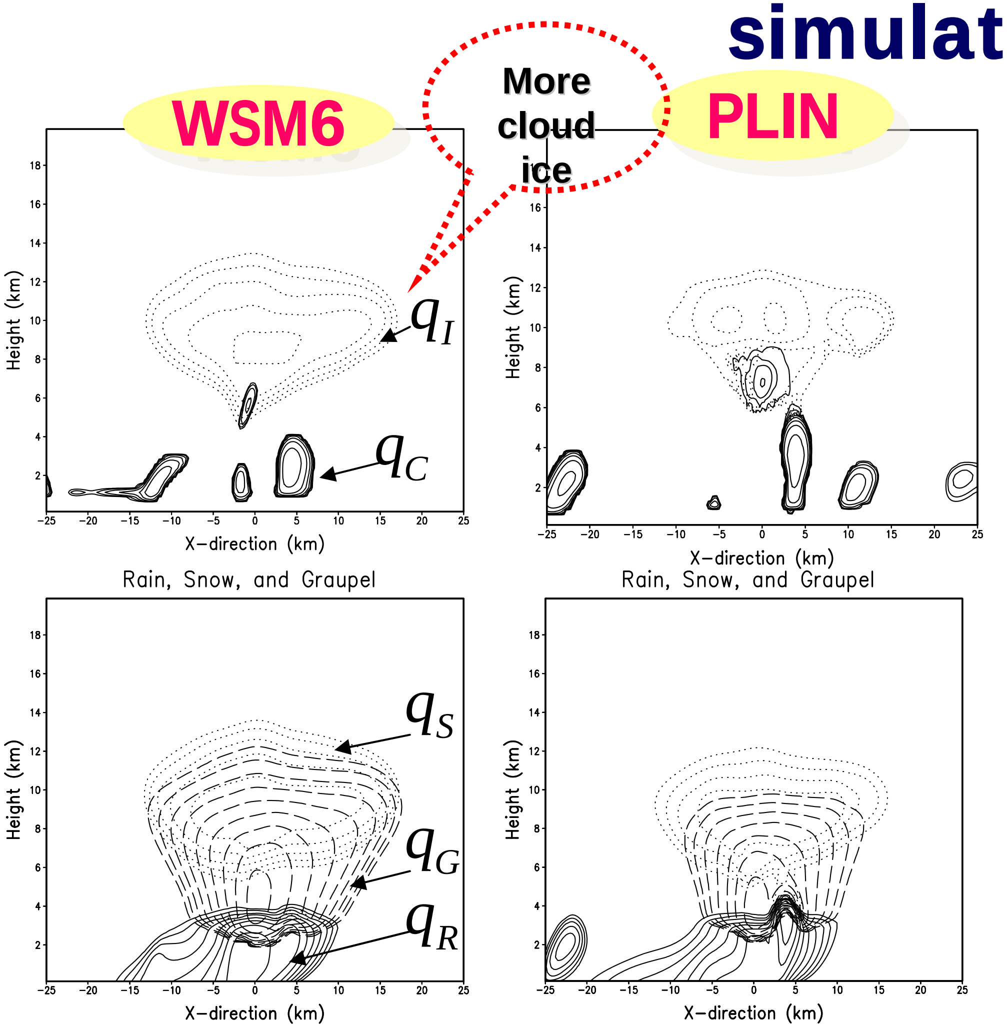
PLIN : PLIN scheme

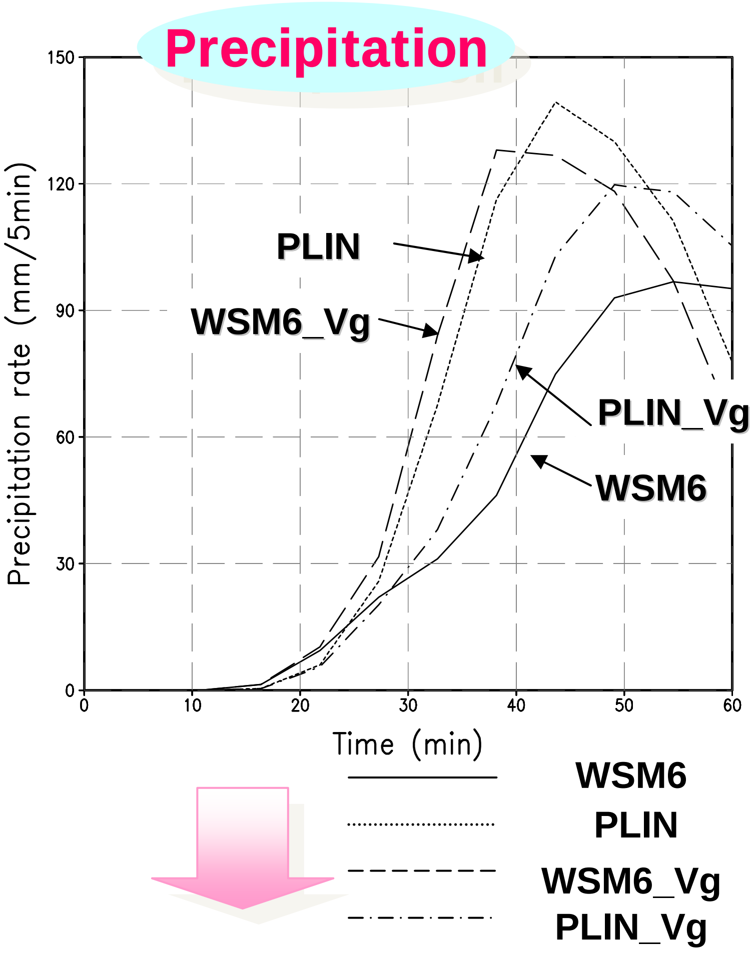
WSM6_Vg : WSM6 scheme but with PLIN Vg

PLIN_Vg : PLIN scheme but with WSM6 Vg

One can tell the importance of microphysics or sedimentation of graupel between the PLIN and WSM6 schemes

Effect of different terminal velocity in idealized simulation

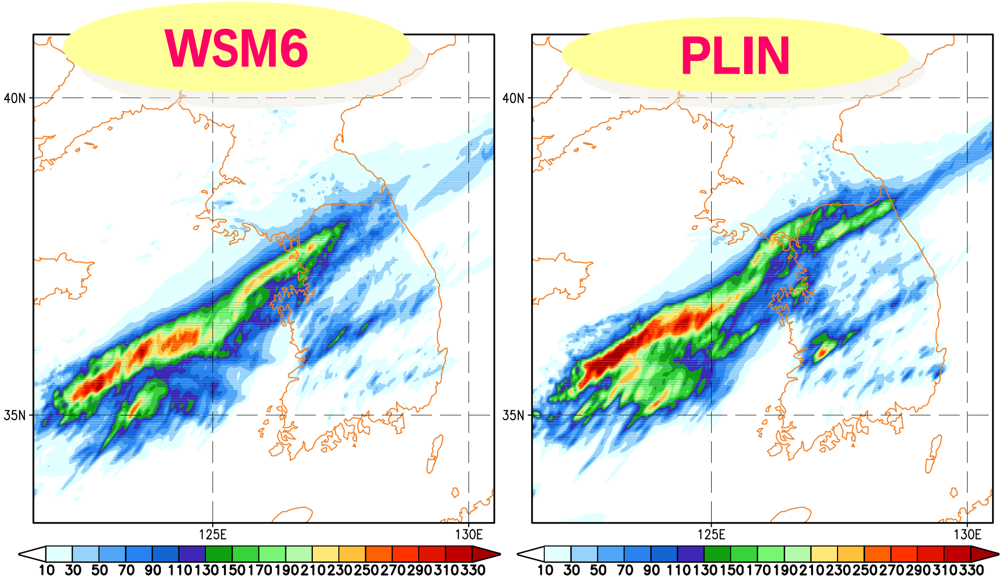


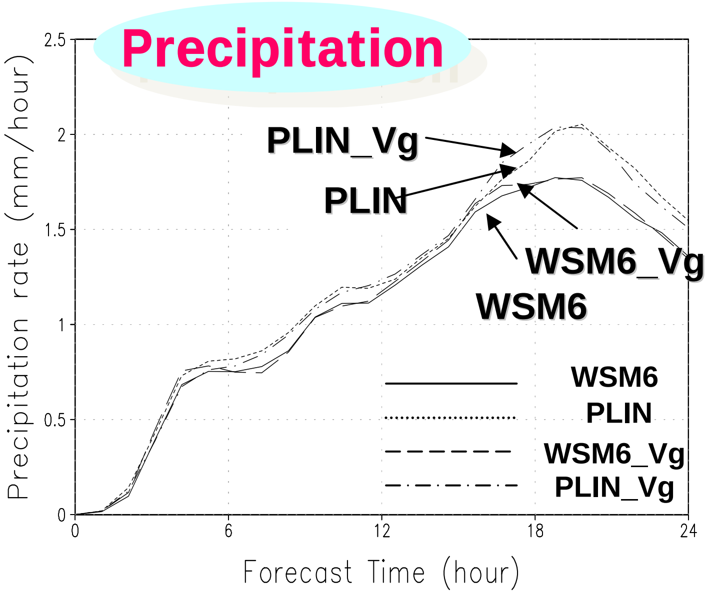


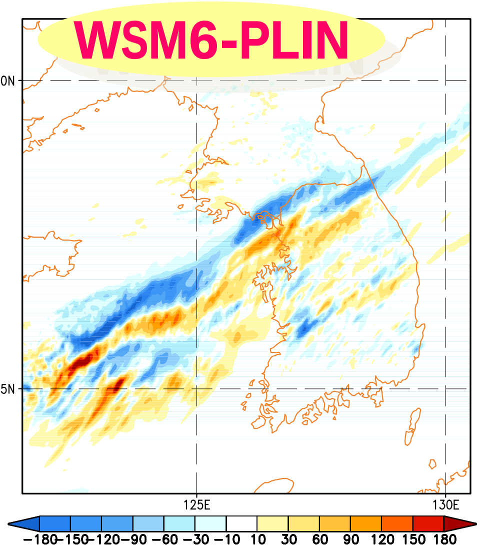
WSM6_ vg and PLIN_vg experiments identify that the evolution of surface precipitation are significantly affected by the magnitude of sedimentation of graupel

Hong et al. (2008)

Effect of different terminal velocity in real case simulation







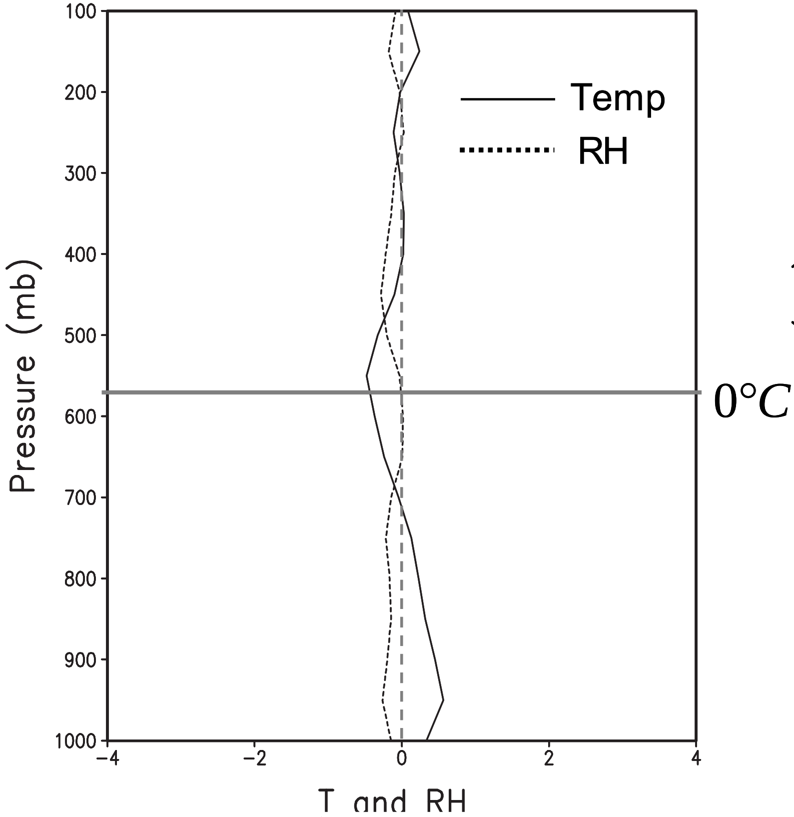
the evolution precipitation from the WSM6_vg run (PLIN_ vg) is very close to that with the WSM6 (PLIN) experiment

Hong et al. (2008)

Changes of the environment due to :

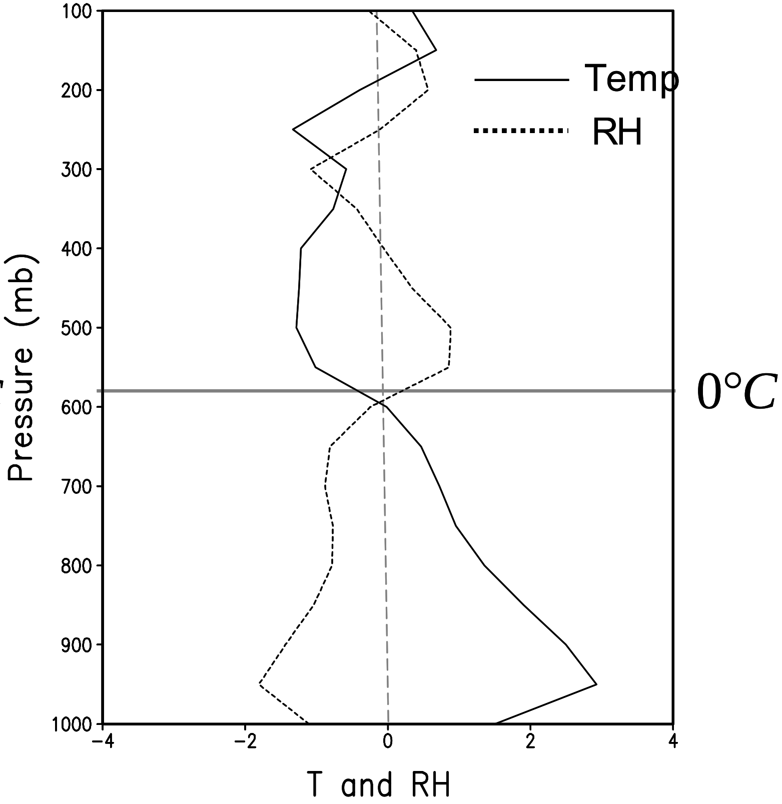
Sedimentation velocity

:WSM6_vg - WSM6



Microphysics

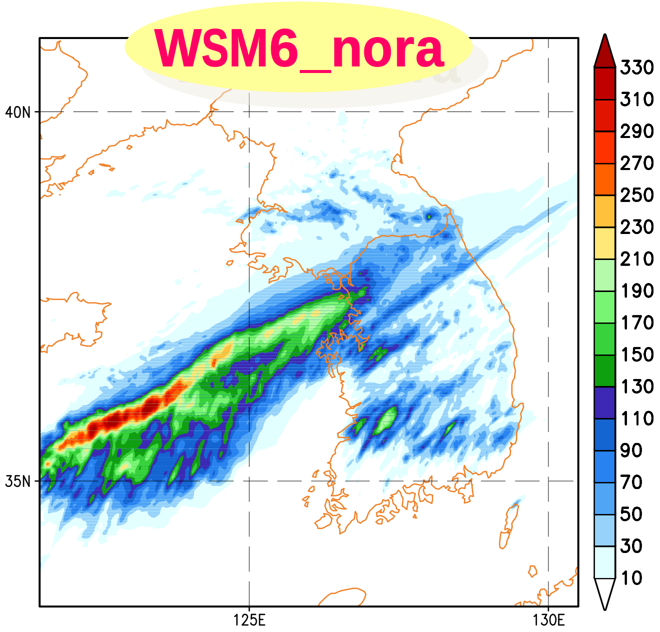
:PLIN_vg -WSM6

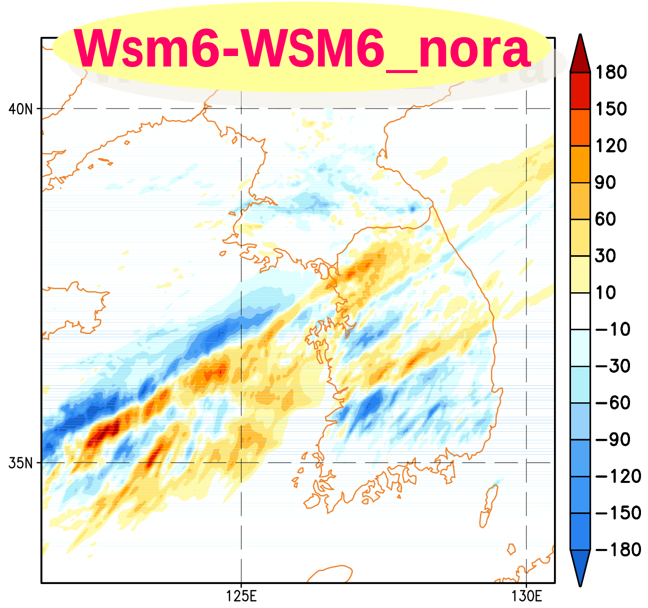


Differences in precipitation in WSM6 scheme is due to the microphysics, rather than the difference in Vg

Hong et al. (2008)

Interaction between the ice clouds and radiation





The WSM6_nora shifts the major precipitation band northward, which is similar to that in the PLIN.

Hong et al. (2008)

Remarks on Vg and ice microphysics

- A reason for the different effect of the terminal velocity of graupel between the 2D and 3D runs can be deduced from the modulation of thermodynamic environments, rather than the sedimentation velocity.

- The more stabilized structure within the entire troposphere in the WSM6 scheme due to the WSMMPs plays a dominant role of the distribution of precipitation

Hong et al. (2008)

A further consideration on the sedimentation of snow and graupel
:
A new method for representing mixed-phase particle fall speeds in the WSM6

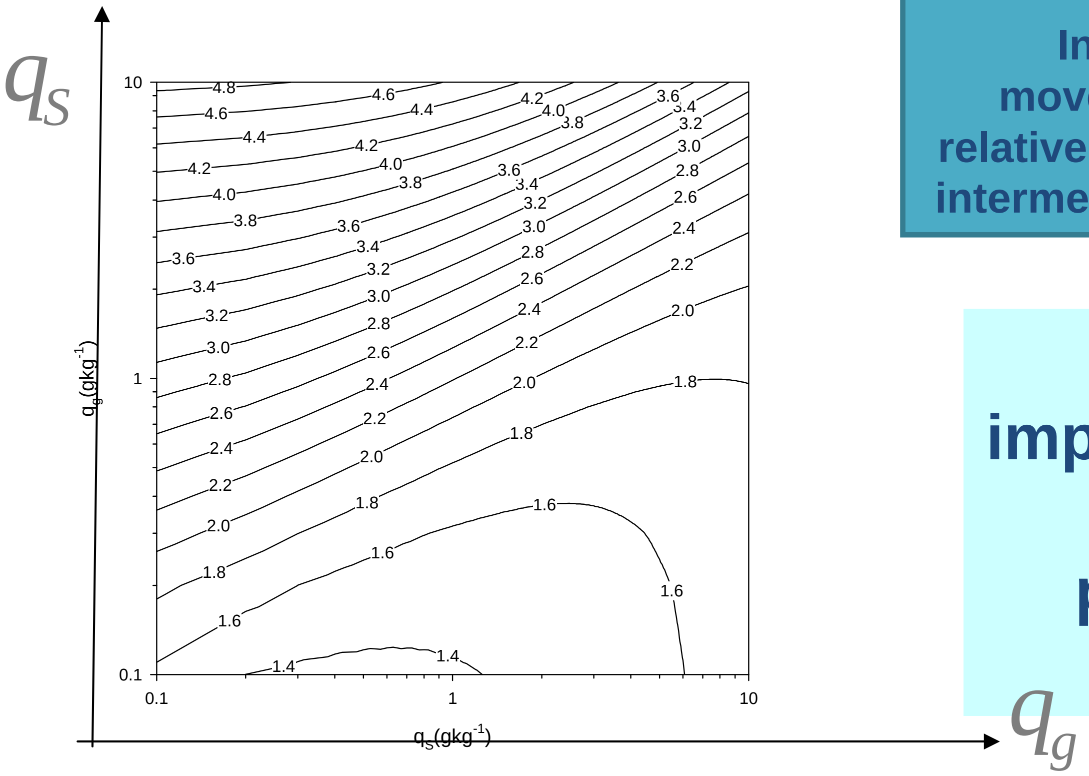
Dudhia, Hong and Lim

(2008, J. Meteor. Soc. Japan)

Dudhia et al. (2008)

A new unified mass weighted terminal velocities for snow and graupel

$$\overline{V}_{gs}\,[\mathrm{m\ s^{-1}}] = \frac{q_s\overline{V}_s + q_g\overline{V}_g}{q_s + q_g}$$



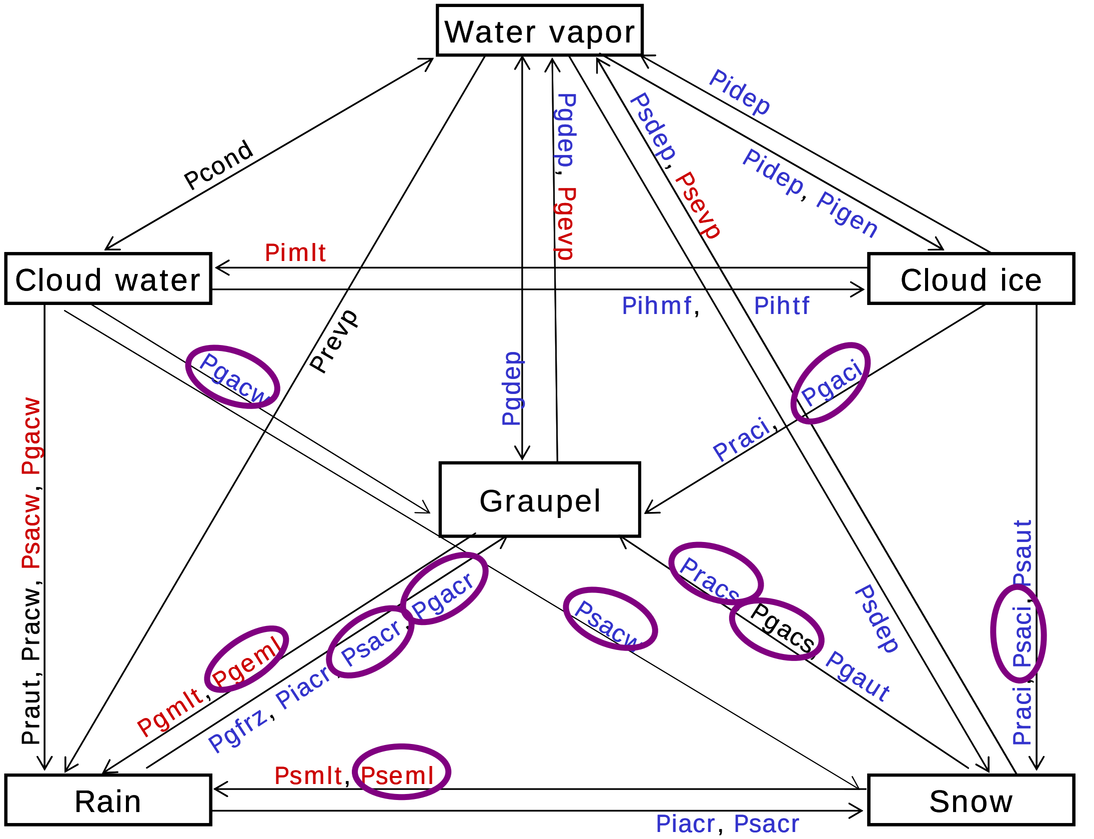
The new Vgs avoid the problem of the species separating out by sedimentation as graupel forms, and the further problem of graupel then accreting snow too quickly because of its higher relative fallspeed.

Instead the unified graupel/snow moves together and evolves in its relative ratio due to riming, behaving as intermediate or partially rimed particles.

It shows promise in improving precipitation intensity and precipitation type forecasts

Dudhia et al. (2008)

Flowchart of the microphysics processes in the WSM6

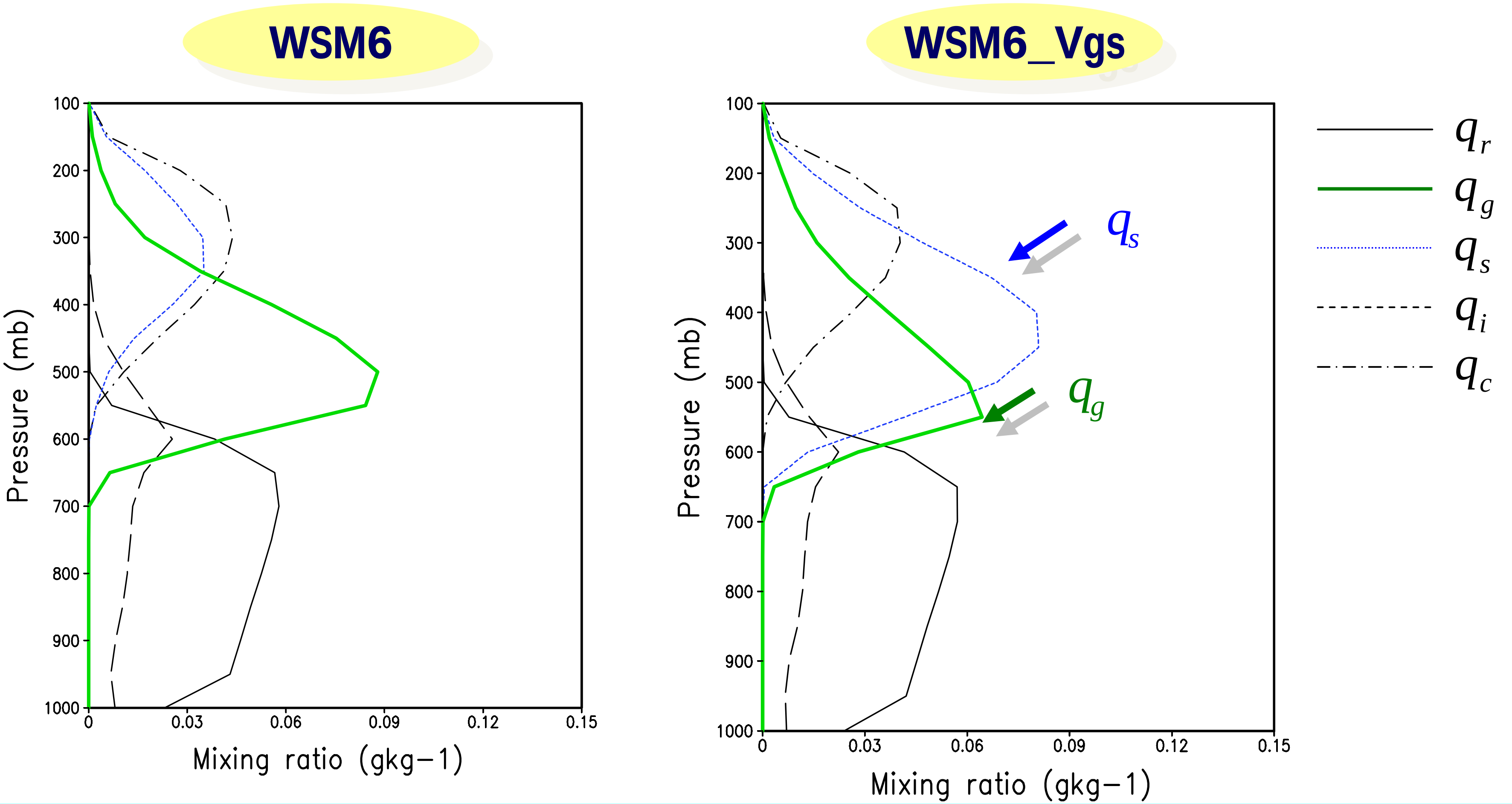


- ⬭ **indicates the changing terms caused by new velocities of graupel and snow**

Dudhia et al. (2008)

Heavy rainfall over Korea during 14-15 July 2001

: Time averaged vertical profiles of hydrometeor



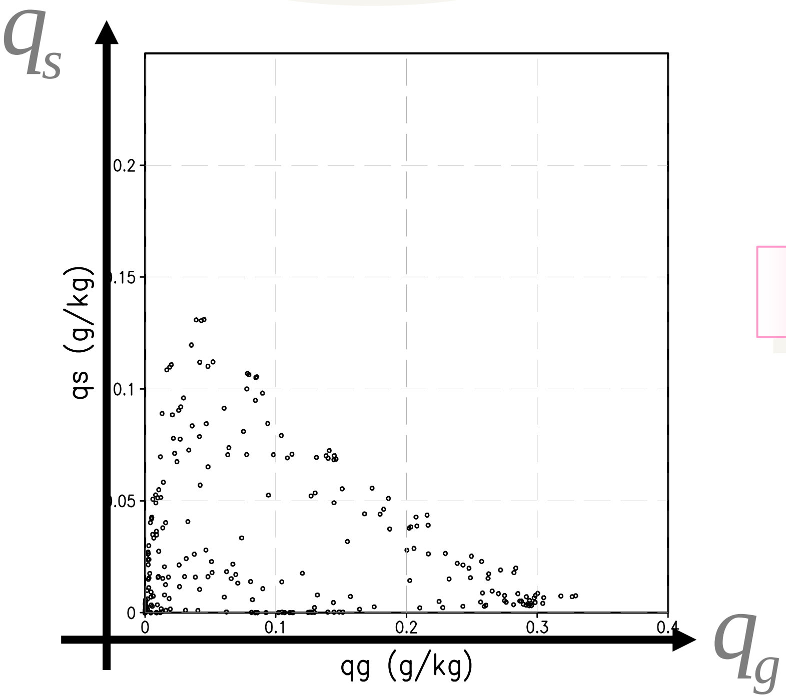
Reduced graupel and increased snow is distinct in the WSM6_Vgs.

Dudhia et al. (2008)

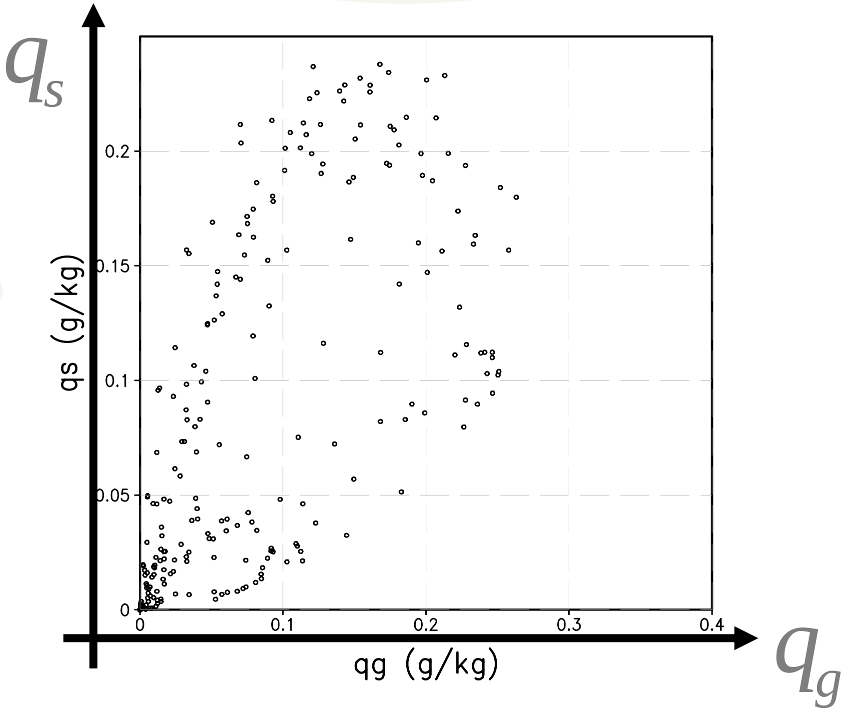
Heavy rainfall over Korea during 14-15 July 2001

: Scatter plot of Qg versus Qs

WSM6



WSM6_Vgs

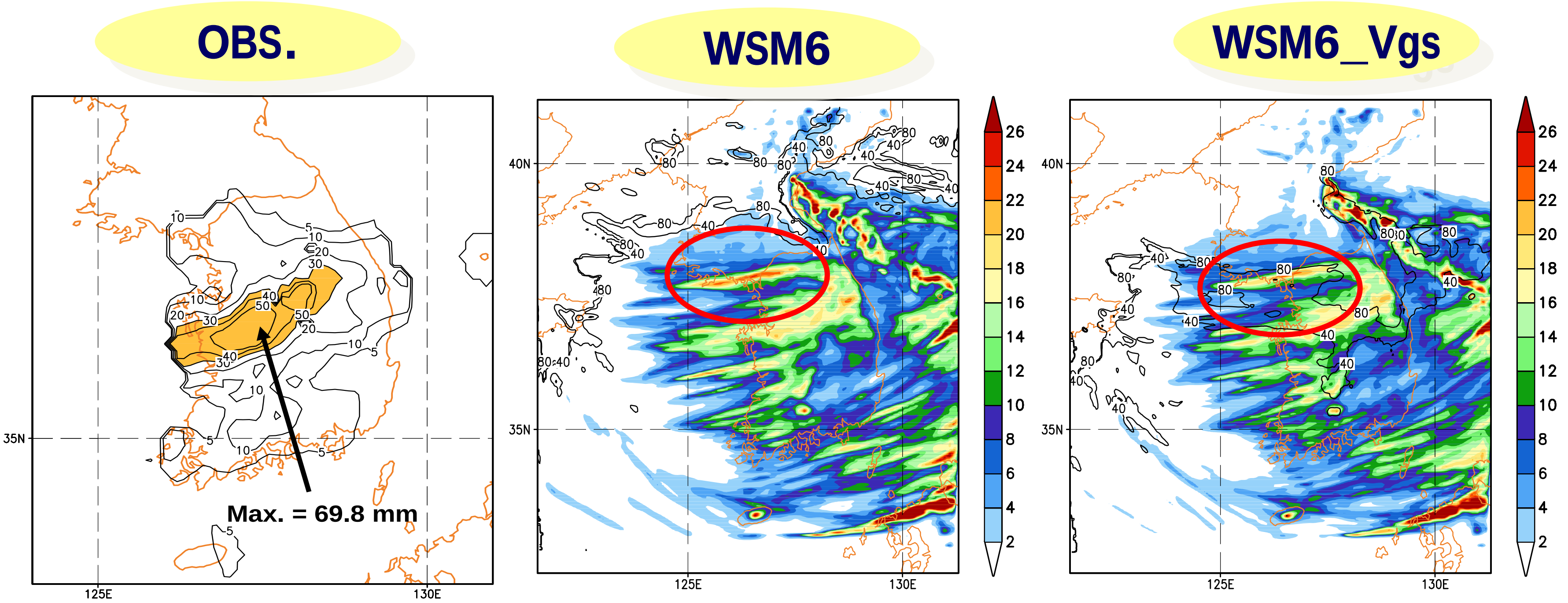


These show that the graupel and snow change from uncorrelated fields to correlated ones because of their unified fall speeds

Dudhia et al. (2008)

Heavy snowfall over Korea during 3-5 March 2004

: Accumulated precipitation



OBS.

WSM6

WSM6_Vgs

Max. = 69.8 mm

similar pattern in the distribution of precipitation,
however more snow amount in the WSM6_Vgs

Dudhia et al. (2008)

Remarks on Vs and Vg

- This scheme is designed to alleviate the effects of the separation of precipitating ice particles into distinct rimed graupel and unrimed snow categories with clearly defined properties and fallspeeds.

- A systematic underestimation of snow and overestimation of graupel in the WSM6 that was indicated by the previous studies (e.g., Lin et al. 2006, Tao et al. 2008) is expected to be alleviated by the introduction of the new falling velocity.

Numerical accuracy of sedimentation

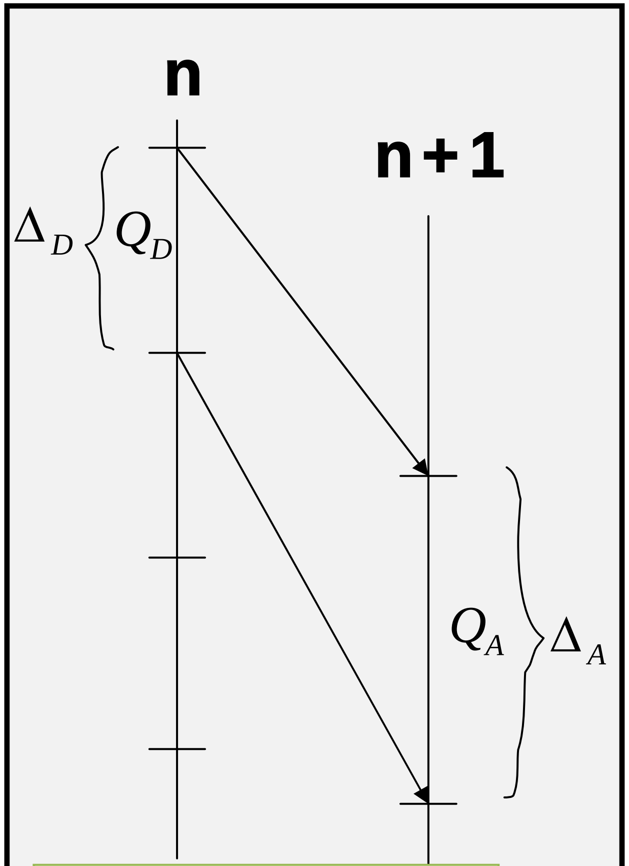
Forward semi-Lagrangian mass conservation positive definiteness advection for falling precipitation

Hann-Ming Henry Juang, Song-You Hong

MWR (2010, May issue)

Non-iteration semi-Lagrangian (NISL) scheme

i) Monotonic advection

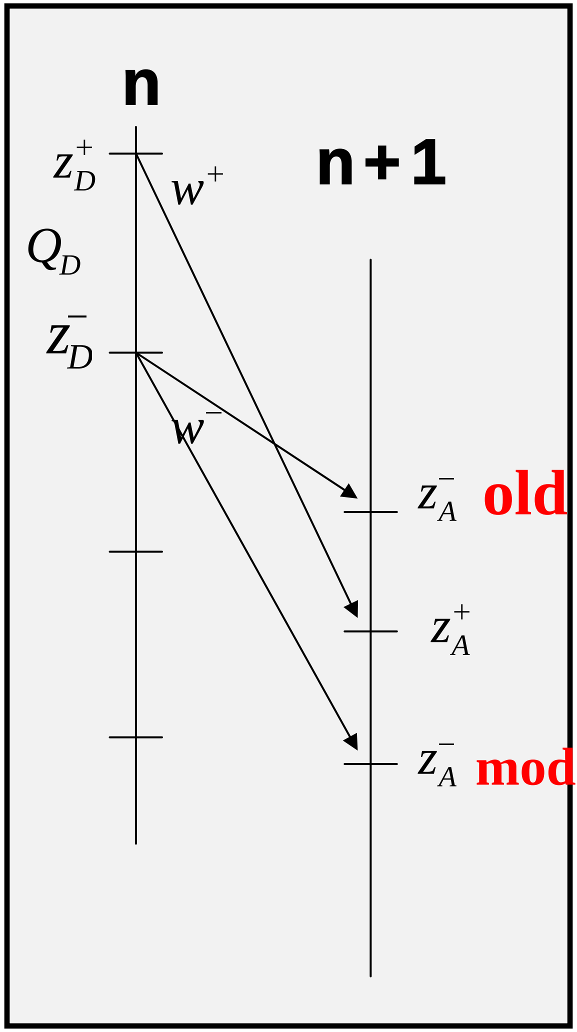


let $Q = \rho q$

$$(Q\Delta)_{arrival} = (Q\Delta)_{departure}$$

$$Q_A = Q_D \Delta_D / \Delta_A$$

ii) Introduce deCFL



$$Q_A(k) >> Q_A(k-1)$$

$$w^+ >> w^-$$

$$\Delta_A < 0$$

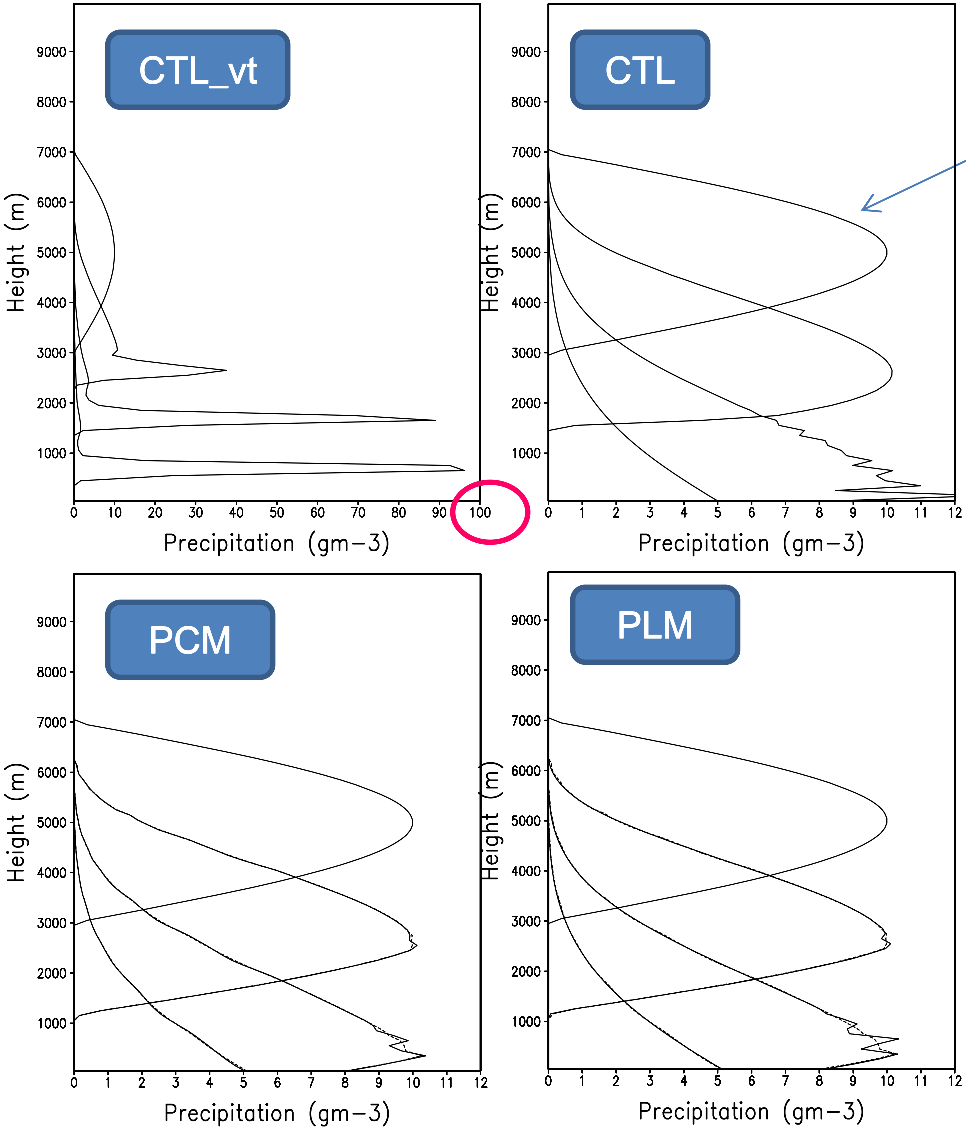
$$deCFL = (w^+ - w^-)\frac{\Delta t}{\Delta_D} > 1$$

Modify $w^- = w^+ - c\frac{\Delta_D}{\Delta t}$

with $c < 1$

WSM3 implementation : 1D case

❖Evolution of Hydrometeors



Hydrometeor Shape at initial time

qr = 10 cos[pi (Zc-Z)/Zd] (g/kg)

dz=100m, Zc=5000, Zd=40dz

Terminal velocity is function of qr

$$V_G[\mathrm{ms}^{-1}] = \frac{a_G\Gamma(4+b_G)}{6}\left(\frac{\rho_o}{\rho}\right)^{\frac{1}{2}}\frac{1}{\lambda_G^{b_G}}$$

Maxima W is about 10 m/s

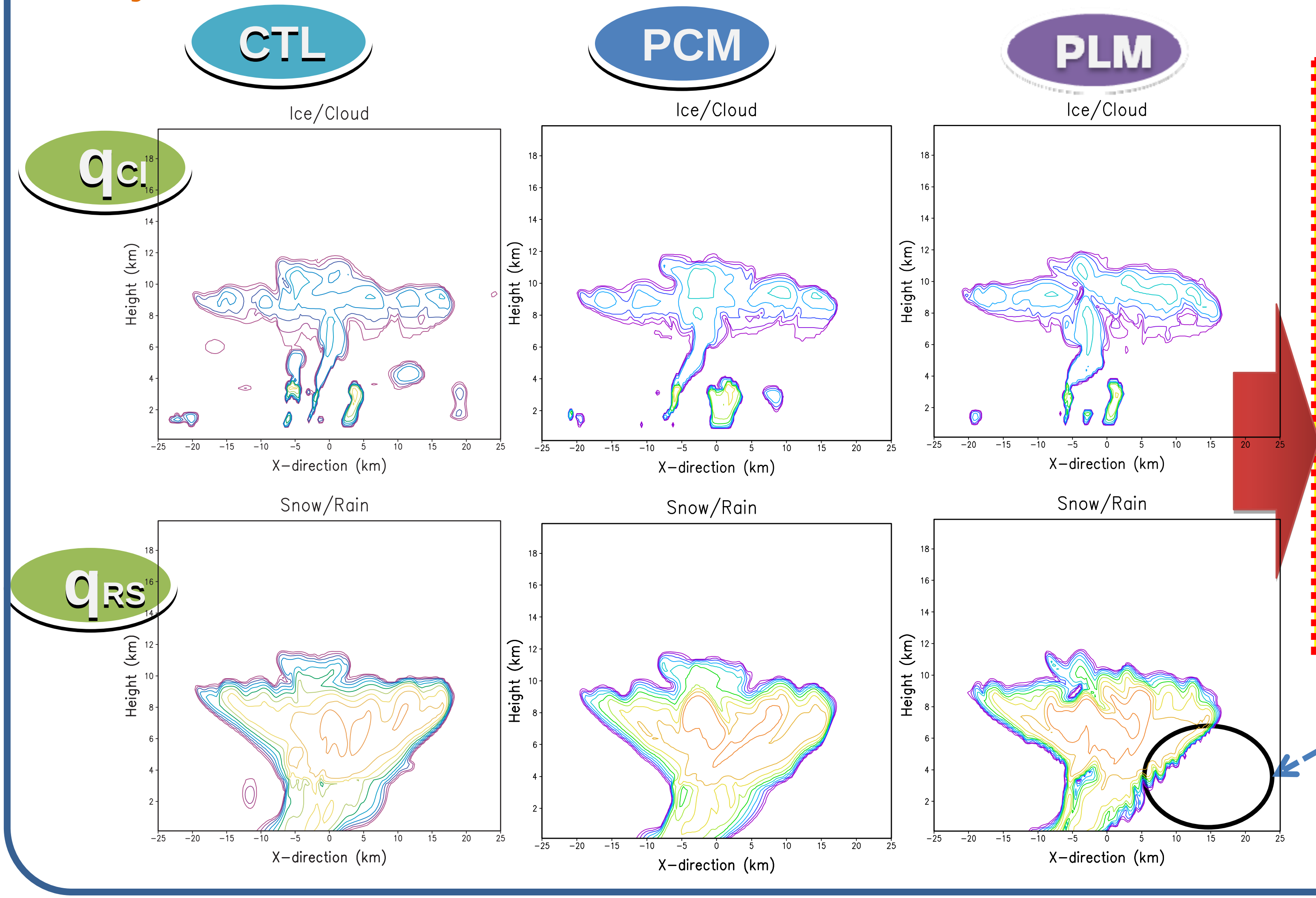
dt=120s CFL=10*120/100 = 12

Current sedimentation in WRF (CTL_vt) : A serious problem

SEMI with PLM is a good choice

Squall-2D experiments

▪Hydrometeors Fields



CTL and PCL are similar. PLM and PPM are similar.

PLM produces a mammatus-like features beneath the anvil clouds.

Remarks on the accuracy of sedimentation

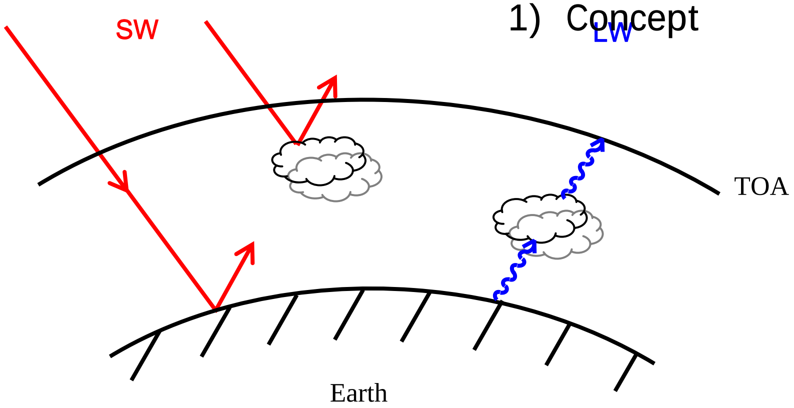
The erroneous sedimentation code has been running without much attention

➔ Surface precipitation for a certain time period is not that strange

Microphysics (precipitation process) – cloudiness - radiation

Overview of radiation parameterization

1) Concept



TOA : S = 1360 Wm^{-1} , $\mathit{Mean\ Flux} : \frac{S}{4} = 340\,Wm^{-1}$

→ Energy source for Earth

30% : reflected from the atmosphere clouds

$\begin{cases} 25\% : \text{absorbed in the atmosphere} \\ 45\% : \text{absorbed at the earth surface} \end{cases}$

→ back to space by terrestrial infrared radiation

$\begin{cases} \text{At low latitude : energy gain} \\ \text{At high latitude : energy loss} \end{cases}$

* Radiational forcing : $Q_a = Q_{as} + Q_{ae}$

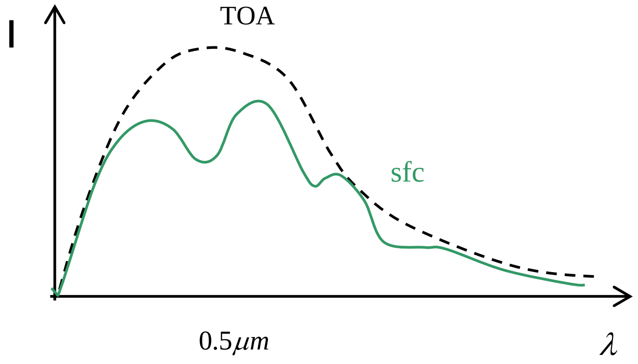
※ $\begin{cases} Q_{as}: \text{heating due to absorption of insolation in the atmosphere} \\ Q_{ae}: \text{heating \& cooling due to infrared radation from the atmosphere} \end{cases}$

◆ Q_{as} : based on radiative transfer theory & depend on the known vertical distribution of absorbing or emitting gases such as $\mathrm{H_2O,\ CO_2,\ O_2,\ O_3}$ and also consider the effects of scattering by atmospheric molecules and aerosols and reflection by clouds.

◆ Q_{ae} : based on radiative transfer theory and the known absorptivity of atmospheric constituents and the vertical distribution of temperature. Radiatively active gases are $\mathrm{H_2O,\ CO_2,\ O_3,\ CH_4,\ CO,\ CFC}$. Both upward and downward fluxes are involved.

→ Handling cloud effects is much more complicated than SW.

2) Solar radiative transfer



- At TOA,

$$F = S\left(\frac{dm}{d}\right)^2 \cos\theta_0 \quad (\theta_0 : \text{Zenith angle}) \qquad \mu = \cos\theta$$

(Insolation)

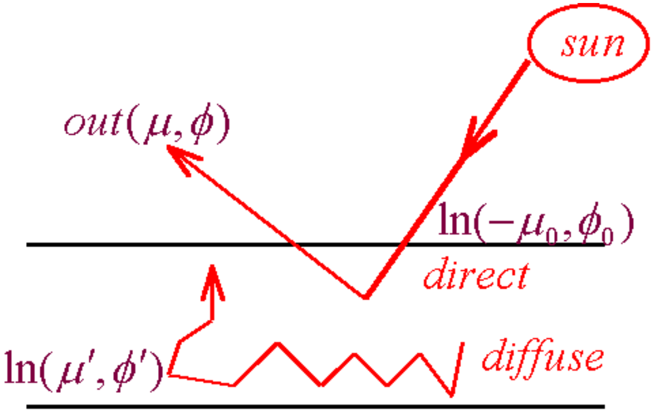
- Basic equations

$$\mu \frac{dI(\tau,\mu,\phi)}{d\tau} = I(\tau,\mu,\phi) - J(\tau,\mu,\phi)$$

absorption source emission

$$\tau\,(\text{optical depth}) = \int_z^{z_\infty} k_\nu (z')\rho_a(z')dz'$$

$$d\tau = -k_\nu \rho_a dz \qquad = \int_0^p k_\nu(p')q(p')\frac{dp'}{g}$$



$$J = J(\tau,\mu,\phi) = \frac{\tilde{\omega}}{4\pi}\int_0^{2\pi}\int_{-1}^{1} I(\tau,\mu',\phi')P(\mu,\phi;\ \mu',\phi')\,d\mu'\,d\phi \text{[diffuse (multiple) scattering]}$$

$$+\frac{\tilde{\omega}}{4\pi}F_0 P(\mu,\phi;-\mu_0,\phi_0)e^{-\frac{\tau}{\mu_0}} \text{[single(direct) scattering]}$$

P : Scattering phase function :redirects $(\mu',\phi') \rightarrow (\mu,\phi)$

$\tilde{\omega} = \dfrac{\sigma_s}{\sigma_e}$: Scatteing albedo

scattering cross section/extinction(scattering + absorption) cross section

* remove ϕ dependency using $P(\cos\theta)$ function

* P, $\tilde{\omega}$, Albedo depend on λ, particle size & shape.

$$P(\cos\phi) = \sum_{l=0}^{N} \tilde{\omega}_l P_l(\cos\phi) \quad \text{: Legendre Polynomial}$$

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\tilde{\omega}}{2}\sum_{l=0}^{N} \tilde{\omega}_l P_l(\mu) \int_{-1}^{1} P_l(\mu')I(\tau,\mu')d\mu'$$

$$-\frac{\tilde{\omega}}{4\pi}\sum_{l=0}^{N} \tilde{\omega}_l P_l(\mu) P_l(-\mu_0) F_0 e^{-\frac{\tau}{\mu_0}}$$

→ The azimuth-independent phase function gives,

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - \frac{\tilde{\omega}}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' - \frac{\tilde{\omega}}{4\pi} P(\mu,-\mu_0) F_0 e^{-\frac{\tau}{\mu_0}}$$

The monochromatic upward and downward diffusion fluxes at a given . τ

$$F_{diff}^{\pm}(\tau) = \int_0^{2\pi}\int_0^{\pm 1} I(\tau,\mu,\phi)\mu d\mu d\phi$$

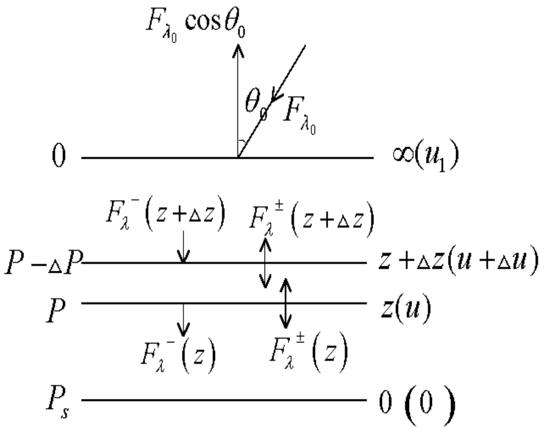
The direct downward solar flux at level . τ

$F_{dir}^{-}(\tau) = \mu_0 F_0 e^{-\frac{\tau}{\mu_0}}$; exponential attenuation

The net flux : $F_s(z) = \underbrace{F^{-}(z)}_{\text{Direct+diffuse}} - \underbrace{F^{+}(z)}_{\text{diffuse}}$

$$\left(\frac{\partial T}{\partial t}\right)_s = \frac{1}{\rho c_P}\frac{dF_s(z)}{dz} = \frac{g}{c_P}\frac{\Delta F_\lambda(P)}{\Delta P} = -\frac{g}{c_P}\frac{\Delta F_\lambda(u)}{\Delta u}$$

$$\left(\frac{\partial T}{\partial t}\right)_{total} = \sum_{s=1}^{N}\left(\frac{\partial T}{\partial t}\right)_s$$



Radiative transfer equation solver.

→

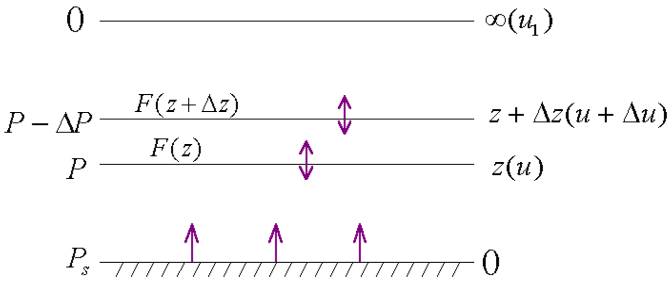
Discrete - ordinates method

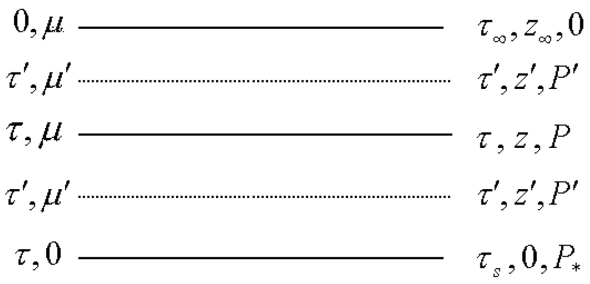
Two - Stream and Eddington's approximation

Delta - function adjustment and similarity principle

δ - Four stream approximation

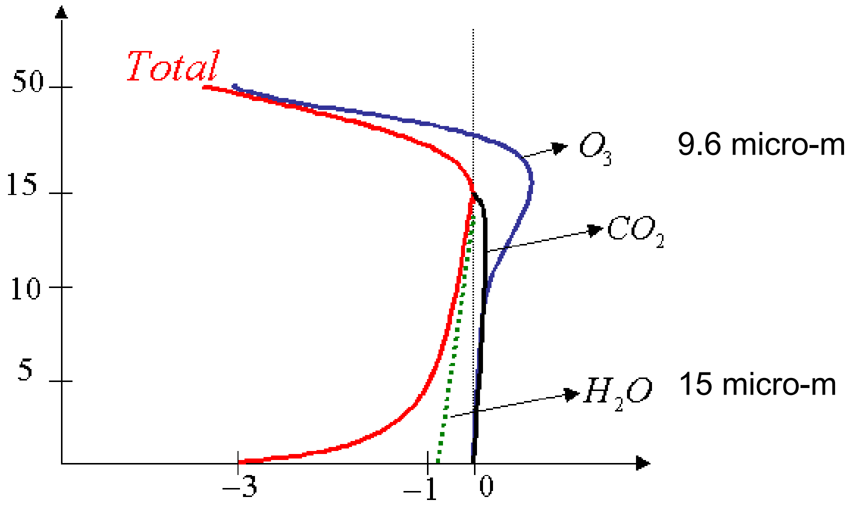
3) Terresterial radiation





$$F(z) = F^{\uparrow}(z) - F^{\downarrow}(z)$$
$$\Delta F = F(z+\Delta z) - F(z)$$

$$\left.\frac{\partial T}{\partial t}\right|_{IR} = -\frac{1}{c_P\rho}\frac{\Delta F}{\Delta P} = -\frac{g}{c_P}\frac{\Delta F}{\Delta u}$$



In spectral bands (monochromatic)

$$\uparrow \quad \mu\frac{dI_\nu(\tau,\mu)}{d\tau} = I_\nu(\tau,\mu) - B_\nu(T)$$

$$\downarrow \quad -\mu\frac{dI_\nu(\tau,-\mu)}{d\tau} = I_\nu(\tau,-\mu) - B_\nu(T)$$

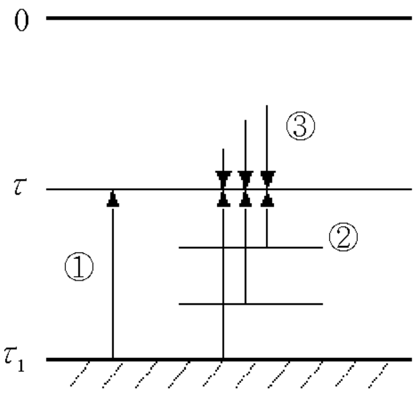
B.C. $\begin{cases} SFC\ (\tau=\tau_1),\ I_\nu(\tau,\mu) = B_\nu(T_s) \\ TOP\ (\tau=0),\ I_\nu(0,-\mu) = 0 \end{cases}$

$$F^{\uparrow}(\tau) = 2\pi B_\nu(T_s)\int_0^1 e^{-\frac{(\tau_1-\tau)}{\mu}}\mu\,d\mu + 2\int_0^1\int_\tau^{\tau_1}\pi B_\nu[T(\tau')]e^{-\frac{(\tau'-\tau)}{\mu}}d\tau'd\mu$$

$$F^{\downarrow}(\tau) = 2\int_0^1\int_0^\tau \pi B_\nu[T(\tau')]e^{-\frac{(\tau-\tau')}{\mu}}d\tau'd\mu$$

$$d\tau = -k_\nu\rho dz$$

$$\tau_1 = \int_0^{u_1} k_\nu du, \qquad u_1 = \int_0^\infty \rho dz$$



4) Cloud fraction

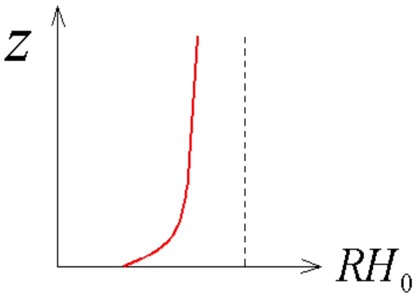
A. Conventional method

$$f = f_c(convective, cumulus - paramet) + f_l(l\arg escale, microphysics)$$

f_c : depends on precipitation, $p_{top,}$ p_{bottom}

f_l : depends on $\mathrm{RH} = 1 - \left[\dfrac{1-RH}{1-RH_0}\right]^{0.5}$

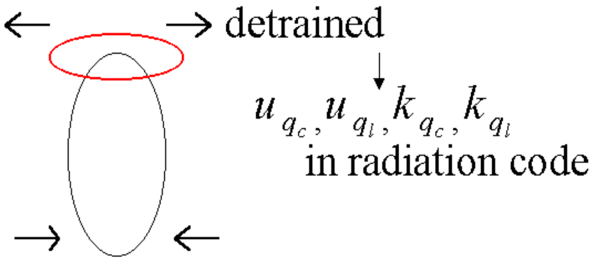
where RH_0 is the critical value of RH which is optimized based on observations. (Slingo's method)



B. Advanced method - inclusion of ice, liquid

- consistent treatment of water substance for both precipitation & radiative properties.

f_c : uses information of detrained water substances from sub-grid scale clouds in convective parameterizations



detrained

$u_{q_c}, u_{q_l}, k_{q_c}, k_{q_l}$

in radiation code

f_l

$q_c, q_s, q_i, \cdots$

i) with diagnostic microphysics (CCM3)

- cloud water scale height r_l

$$h_1 = a\ln(1.0 + \frac{b}{g}\int_{P_T}^{P_S} q\,dp)$$

- cloud droplet size,

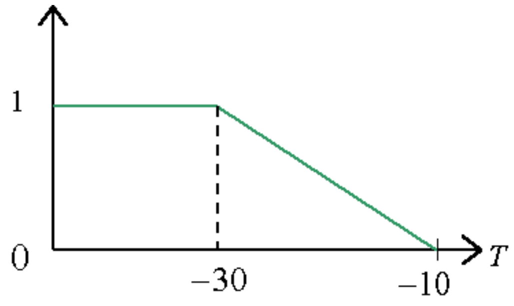
$$r_{ee}\begin{cases} = 10\mu m & \text{over ocean} \\ < 10\mu m & \text{over land} \end{cases}$$

$\cdots$ warm cloud

r_{ei}: $10\mu m \sim 30\mu m$
(low) (high)

$\cdots$ ice cloud

f_{ice} : ice fraction



- The radiation properties of ice cloud in the short wave spectral region :

$$\tau_i^c = \boxed{cwp}[a_i + \frac{b_i}{r_{ei}}]\, f_{ice} \quad \text{(optical thickness)}$$

$$w_i^c = 1 - c_i - d_i \boxed{r_{ei}} \quad \text{(co-albedo)}$$

$$g_i^c = e_i - f_i \boxed{r_{ei}} \quad \text{(asymmetry factor)}$$

$$f_i^c = (g_i)^2$$

a-f : coeff : depends upon band and k-

$$\overline{\tau_c} = \sum_i \tau_i \qquad i: \text{each gas}$$

(The effective optical thickness for each spectral band)

- The long wave cloud emissivity (E_{cld})

$$c_f' = E_{cld} c_f$$

$$E_{cld} = 1 - e^{-Dk_{abc}cwp}$$

※ $D = 1.66$:diffusivity factor

k_{abc} : LW absorptivity coefficient.

$= k_l (1 - f_{ice}) + k_i f_{ice}$

ii) with prognostic microphysics (MM5, WRF ?)

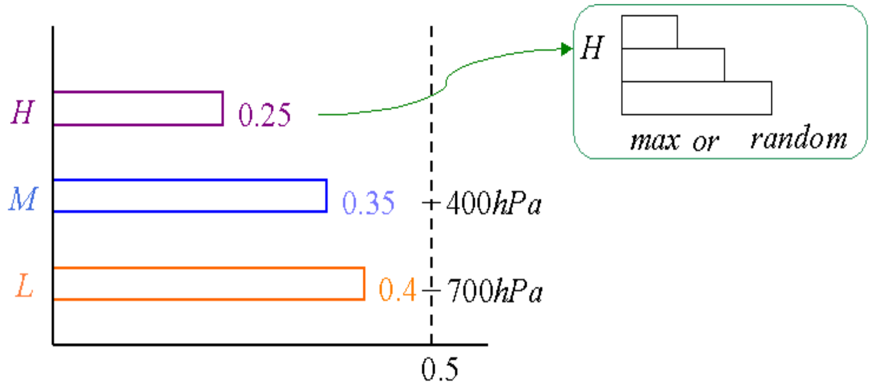
α_p (absorption coefficient)

$$= \frac{1.66}{2000} \left(\frac{\pi N_0}{\rho_{rs}{}^3}\right)^{\frac{1}{4}} \quad m^2 g^{-1} = \begin{bmatrix} 2.34 \times 10^{-3} \quad m^2 g^{-1} \text{ for snow} \\ 0.33 \times 10^{-3} \quad m^2 g^{-1} \text{ for rain} \end{bmatrix}$$

- u_p (effective water path length)

$$= (\rho q_{rs})^{\frac{3}{4}} \Delta z \times 1000 \quad gm^{-2} \quad \rightarrow \tau_p \text{(transmission)} = \exp(-\alpha_p u_p)$$

c) Cloud overlapping



Max. 0.4

Min. 1.0

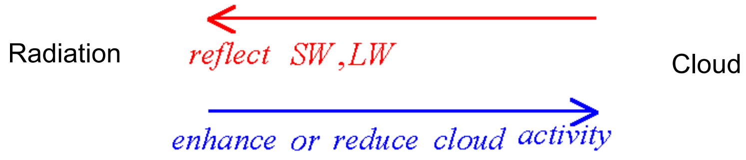
Random : $H + (1 - H)M + \{1 - H - (1 - H)M\}L = 0.6$

τ is scaled by A_c (cloud cover) at a given layer.

- Flux for each of $A_c, (1 - A_c)$ → summation

※ In very high resolution A_c = 0 or 1

In WRF, A= 0, 1



Radiation

reflect SW, LW

Cloud

enhance or reduce cloud activity

Ice-cloud radiation interaction in GCM

WSM1 (diagnostic) → WSM3 (prognostic)

1. saturate vapor pressure respect to the water of ice phase
2. increased number of hydrometeors
3. fractional cloudiness
4. ice-cloud in radiation
5. inclusion of detrainment of cloud water from the convective cloud

Hong et al.

(2010, Asia-Pacific J. Atmos. Sci.)

Global/Regional Integrated Model system (GRIMs): Hong et al. (2010, in preparation)

Dynamics	Spherical Harmonics : Juang (2005), Kanamitsu et al. (2002) Double Fourier Spectral : Cheong (2006), Park et al. (2008, 2010)				
Physics version	GRIMS-phys1 (R2)	GRIMS-phys2	GRIMS-phys3	GRIMS-phys4	GRIMS-phys5
Radiation	SW : 1-Albedo LW : GFDL	NEWALB: SW : 4-Albedo (GSFC) (Chou and Suarez 1999; Chou and Lee 2005; Ham et al. 2009)			SW : GSFC. LW: RRTMG ---WRF
SFC	M-O similarity Hong and Pan (1996)	+ Z0t and Vsfc Seol and Hong (2006)	+ WRF OML (Pollard) +Diurnal SST (Zeng and Beljaars) Kim and Hong (2010)	+ Revised Ch, Cm Kim and Hong (2010), Donlean et al. (2004)	
LSM	OSU1 Mahrt and Pan (1985)	OSU2 Kang and Hong (2008)	NOAH + Seol et al. (2010), Chen and Dudhia (2001)		
PBL	MRF Hong and Pan (1996)	YSU Hong et al. (2006)	YSU + stable BL: Hong (2010)		
GWDO	Alpert et al.(1989)		Kim and Arakawa (1995), Hong et al. (2008)		
GWDC	x		Chun and Baik (1998), Jeon et al. (2010)		
Deep Convection	SAS (Hong and Pan 1998, Park and Hong 2007)			SAS Byun and Hong (2007)	
Shallow convection	Tiedke (1989)			SAS : Han and Pan (2007)	
Micro Physics	WSM1 : Hong et al (1998)				WSM3 Hong et al. (2004)
Cloudiness	Implicit : Hong et al. (1998)				Explicit
Chemistry	Diagnostic			Prognostic ozone	

Physics Development Strategy

Resolution: grid size from 200 m to T62 (200 km)

Model: GRIMSs (SCM, GSM, RSM), and WRF

Single column Model : Direct impact of the new physics

TOGA COARE, ARM, etc.

Regional NWP : Impact on daily forecast

14-15 July 2001, 23-25 June 1997 heavy rainfall

Regional climate : RCM with reanalysis boundary condition

JJA 2002, 2003 East-Asian monsoon, 25-yr climatology

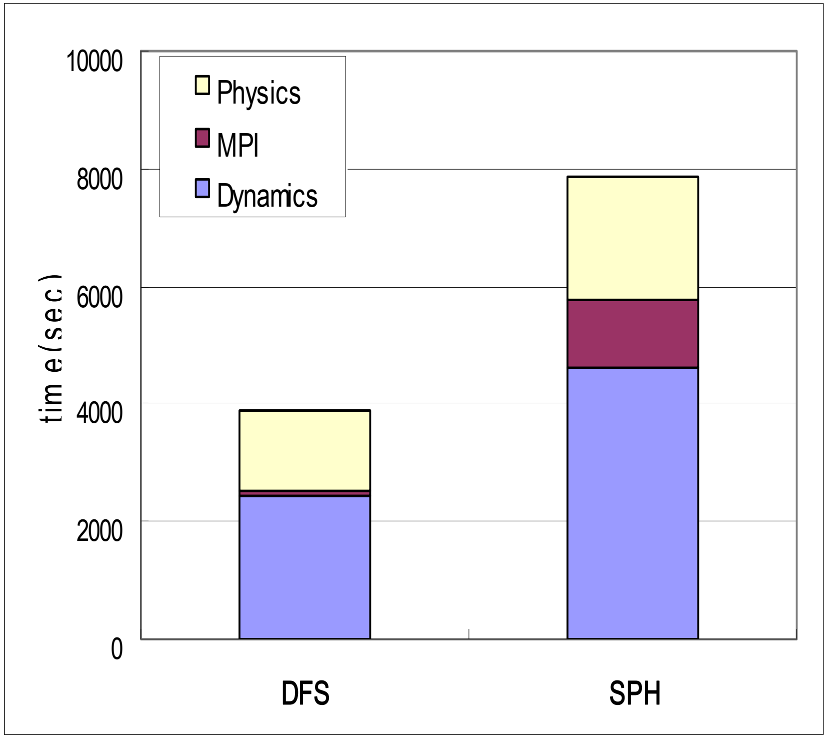
Global NWP : heavy rainfall events, GSM with reanalysis initial data

January 2006, July 2006

Seasonal simulation : Stability of the scheme, tropical precipitation

1996, 1997, 1999 summer and winter , AMIP run

Runtime comparison (T214, MPI)



- T214/L42 (648 x 324)
- 24 hour prediction
- 32 PE (4 nodes with 8 cups) in 2D decomposition
- Dual core Opteron 2.4GHz CPU
- PGI FORTRAN compiler with same compiler options
- SPH Dynamics costs more than DFS by about **200% computation** for T214

- **Wave transpose and load imbalance by computation cost affect on MPI efficiency**

Park et al 2008

Experimental design

Hong et al. (2010)

Summary of experiments

CNTR	Diagnostic cloud (RA2 microphysics)
PRGC	Prognostic q_{ci} and q_{rs}
CLDN	Same as the PRGC, except for the inclusion of hydrometer in cloudiness (Xu and Randall)
ICER	Same as the CLDN, except for the inclusion of ice properties in radiation
DETC	Same as the ICER, except for the inclusion of detrainment of cloud water from the convective cloud

Microphysics Scheme **(number of prgnostic water substane)**

WSM1 (diagnostic) : qv

WSM3 (prognostic) : qv, qc/qi, qr/qs

Hong et al. 1998, 2004

Fractional cloudiness

Slingo 1987 : CNTR, PRGC

Xu and Randall 1996 : CLDN, ICER, DETC

Microphysics effect : CNTR & PRGC

Cloudiness effect : PRGC & CLDN

Ice-cloud effect : CLDN & ICER

Detrainment effect : ICER & DETC

Hong et al. (2010)

Fraction Cloudiness in model

Slingo 1987 : CNTR, PRGC

Xu and Randall 1996 : CLDN, ICER, DETC

- WSM1: **Slingo (1987) : RA2 formula**

$$C_f = 1 - [\frac{1-RH}{1-RH_0}]^{0.5}$$

RH_0 **: critical value of relative humidity (depends upon the height of clouds)**

It can be high even when cloud/ice water does not exist !

- WSM3: **Xu and Randall (1996) : GFS formula**

$$C_f = RH\left[1-\exp\left(\frac{-1000q_t}{1-RH}\right)\right]$$

q_t **: the mixing ratio for total liquid species**

It effectively reduces the cloud fraction in cold clouds where cloud ice is small !

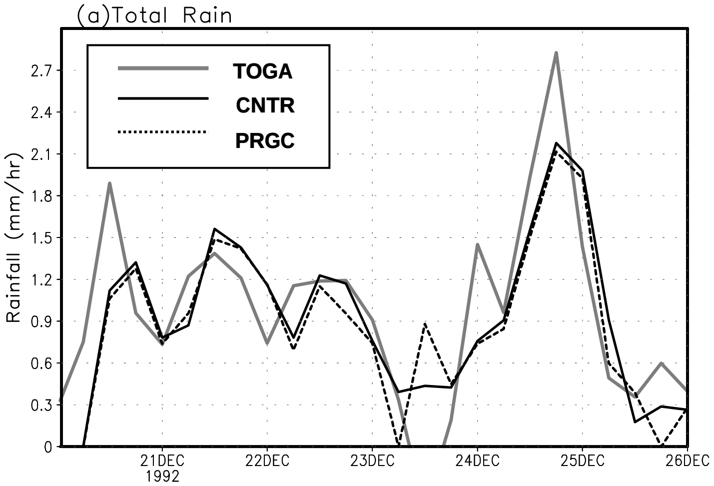
Hong et al. (2010)

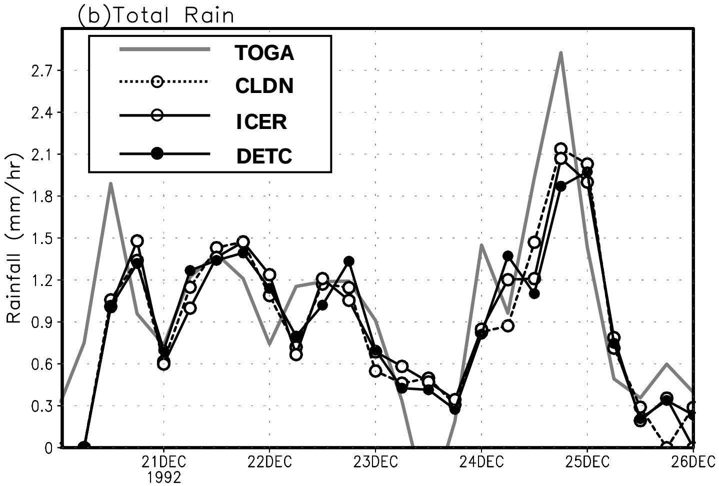
Single column model

Results

Precipitation

Hong et al. (2010)





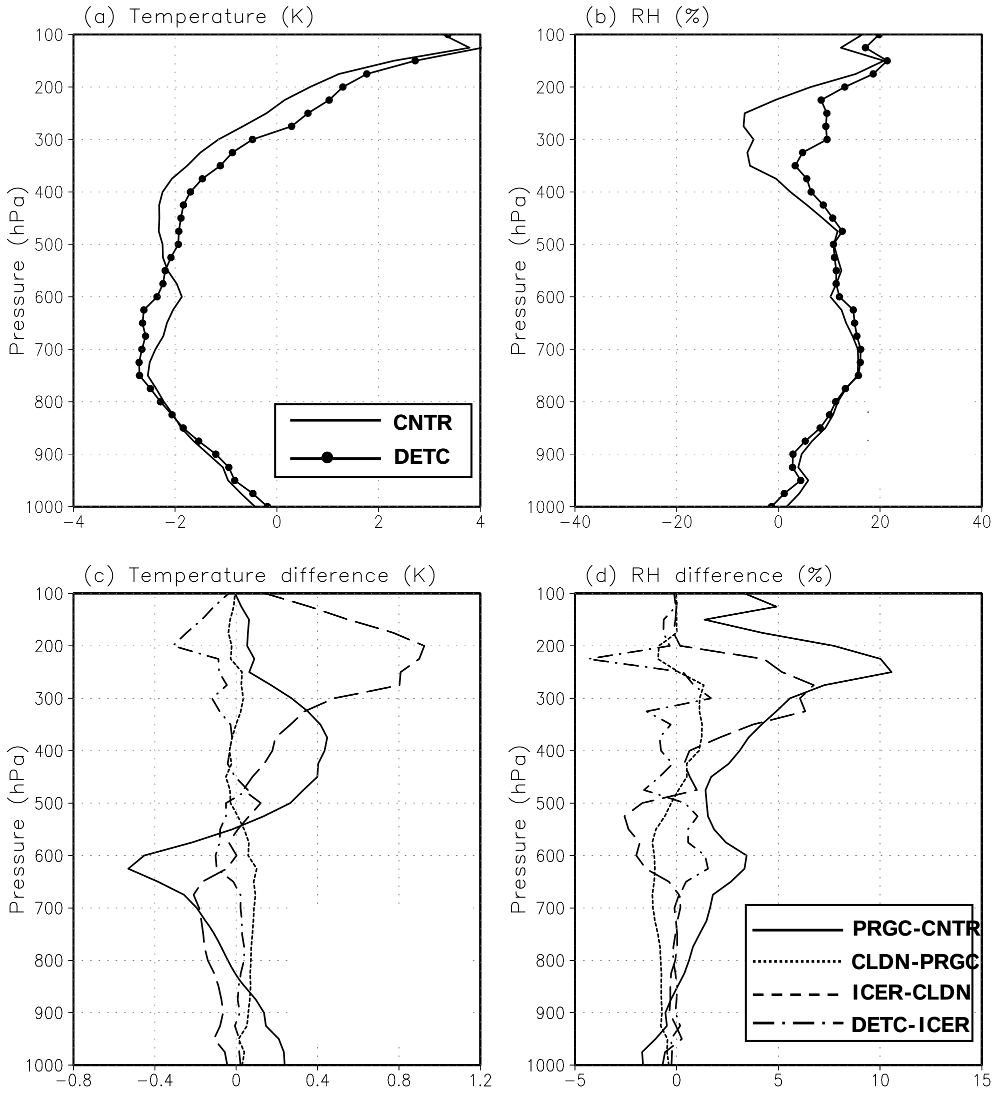
EXP	Total rain (A)	Large-scale rain (B)	Correlation coefficient
TOGA	23.9	-	-
CNTR	23.5	0.7	0.77
PRGC	21.4	0.3	0.70
CLDN	21.6	0.2	0.75
ICER	21.7	0.1	0.71
DETC	21.8	0.1	0.71

Underestimation of rainfall

The experiments using the WSM3 scheme :
decrease of the large-scale precipitation

CNTR : the best correlation coefficient

Temp. & RH



CNTR :

cold and moist

DETC :

warm and moist (200-500 hPa)

cold (550-800 hPa)

Microphysical effect :
cooling (low), warming (upper)

Ice-cloud effect :

warming and moistening (upper)

Cloudiness, detrainment effect :

not dominant

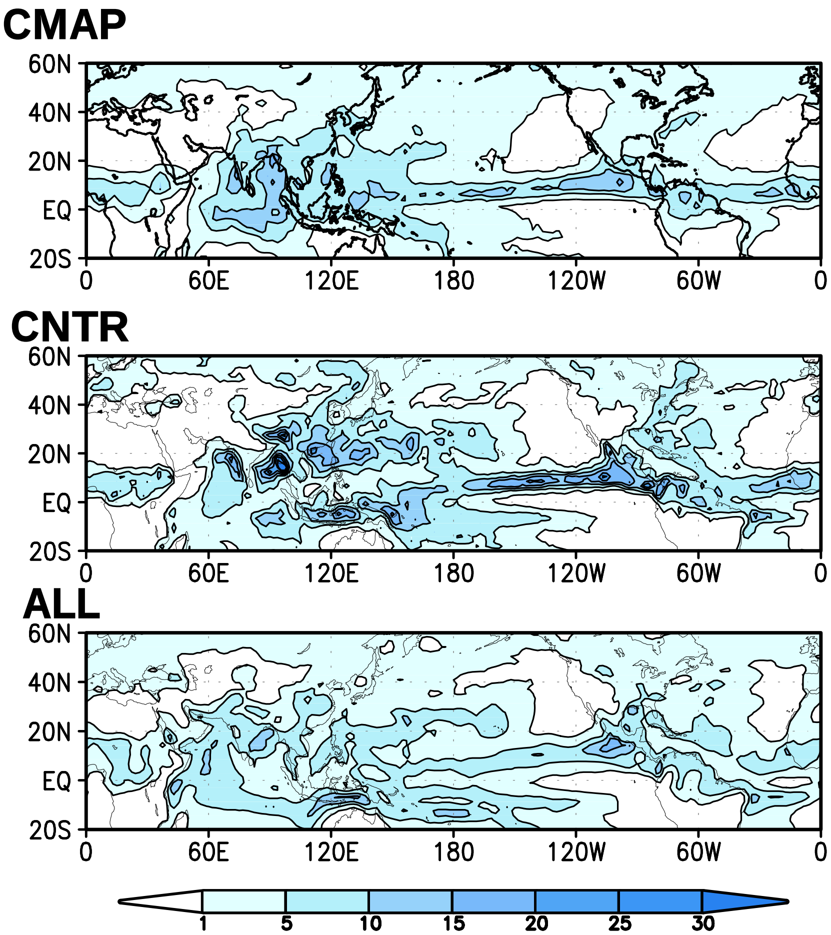
Hong et al. (2010)

Seasonal simulation

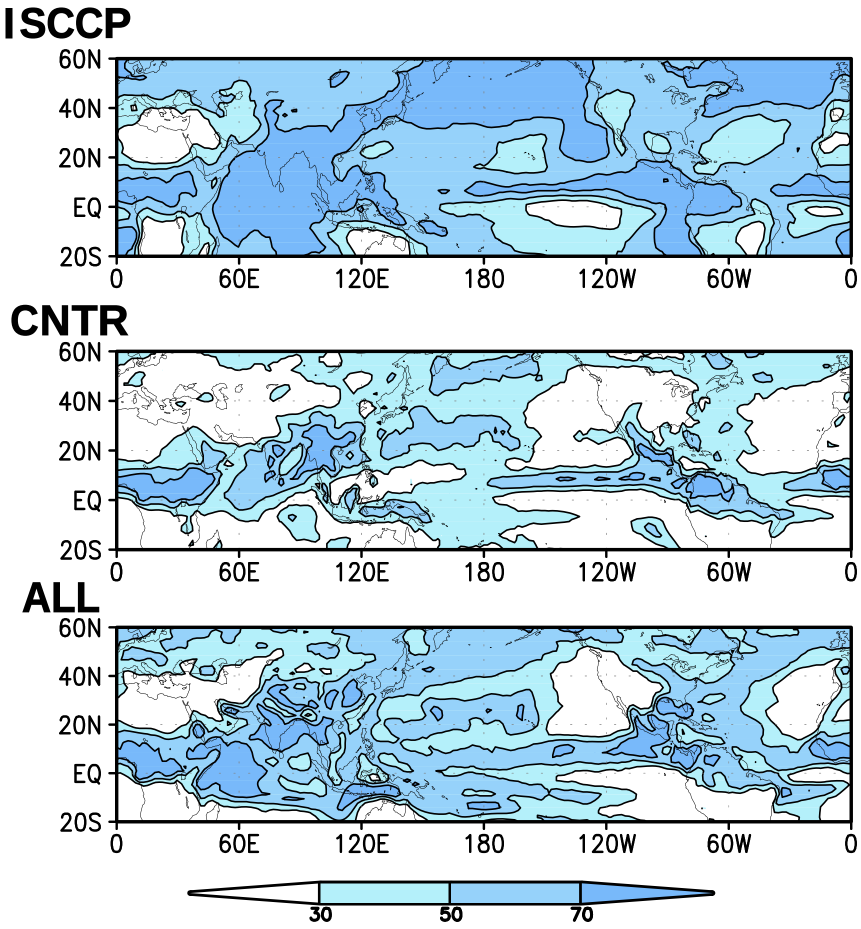
Results

Hong et al. (2010)

Precipitation



Total cloud amount



CNTR– Double ITCZ pattern, overestimation

DETC– significantly decrease of rainfall

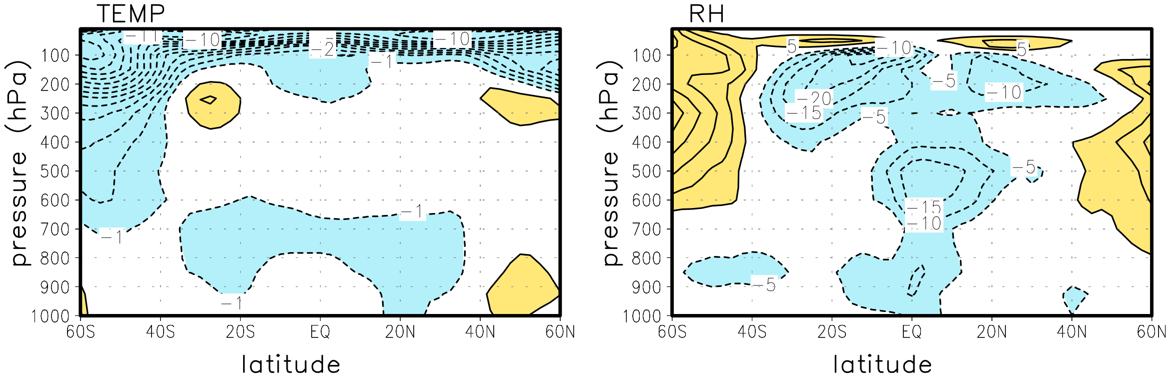
CNTR– underestimation about 20 %

DETC– increase of total cloud amount

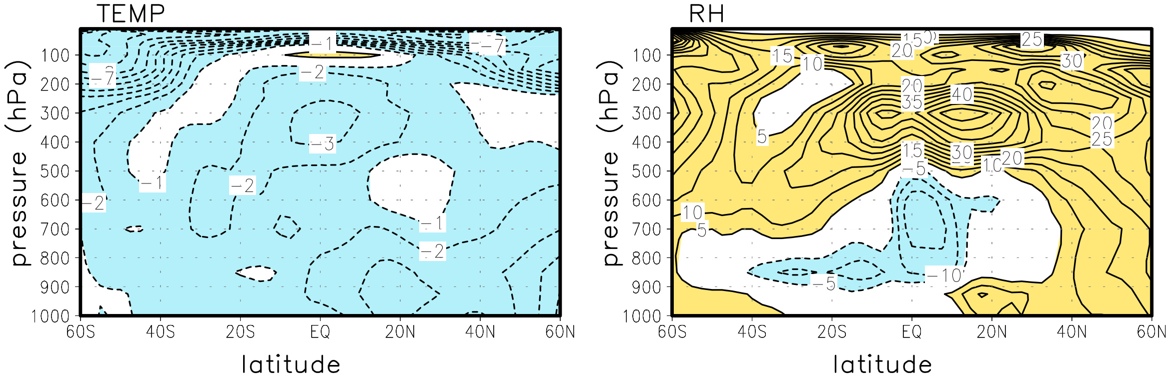
Hong et al. (2010)

Temp. & RH (difference from RA2)

CNTR– RA2



ALL– RA2



CNTR– cold bias

low lat. – dry

mid lat. – moist

ALL – more cooling

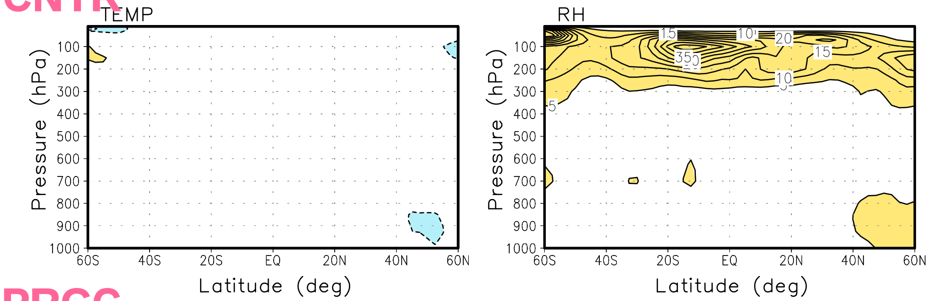
& moistening

decrease of precipitation

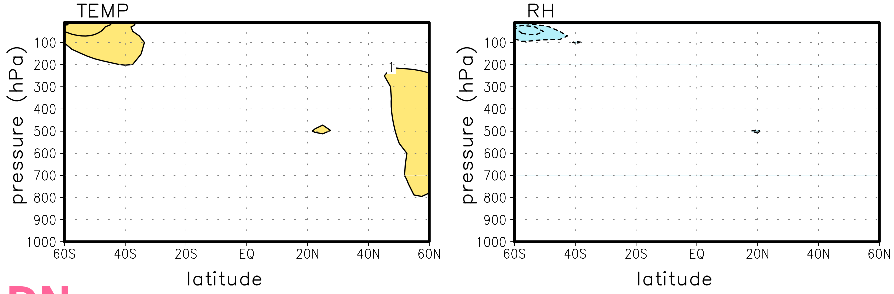
(decrease of convection → moistening in upper level

Hong et al. (2010)

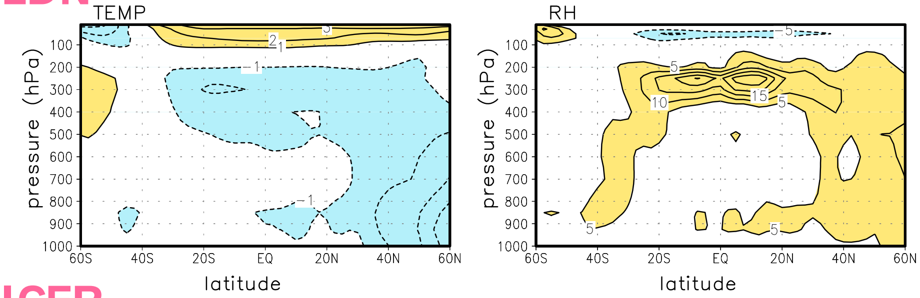
PRGC-CNTR



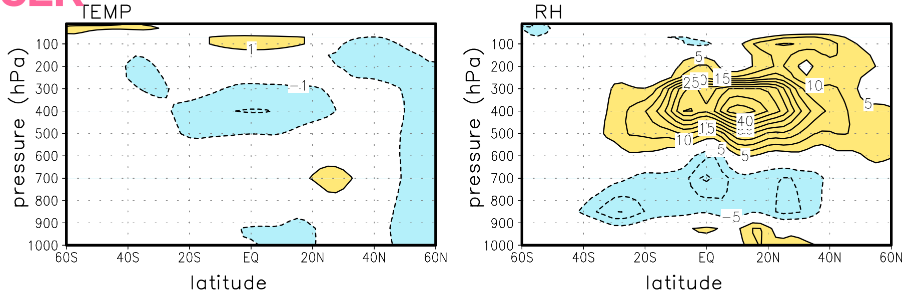
CLDN-PRGC



ICER-CLDN



DETC-ICER



Microphysical effect:

moistening in the upper troposphere

WSM3: complex physics

Hong et al. 1998, 2004

Cloudiness effect:

not significant

Grabowski 2003

Xu and Krueger 1991

Ice-cloud effect:

cooling and moistening in the troposphere

warming and drying in the stratosphere

Ping et al. 2007

Detrainment effect:

Cooling and moistening in the upper troposphere

Comparison of Four Cloud Schemes in Simulating the Seasonal Mean for AMIP Type Integrations

Akihiko Shimpo[*1], **Masao Kanamitsu**[*1]

Sam Iacoballis, and Song-You Hong[*2]

Monthly Weather Review (2008)

Contents

- Introduction
- Objective
- Tested cloud schemes
- Comparison and validation of cloud schemes with ISCCP, ERBE, GPCP observations and R-2 reanalysis.
- Suggest possible revision to cloud parameterization.
- Conclusion

Objectives

- Compare cloud water prediction schemes and cloudiness parameterizations in Global model.
- Focus on stratiform clouds
- Validate simulations with observational data.
- Examine DJF, JJA seasonal mean (10 year average)

Cloud schemes in ECPC G-RSM

	Cloud water prognostic variables(#)	**Stratiform clouds**	Convective clouds	Boundary layer clouds	effici-ency
CNTL	None (0)	**Diagnosed from RH** (SS91)	Diagnosed from convective precipitation (SS91)	Diagnosed from inversion strength and RH (SS91)	100%
ZC	qc/qi (1)	**Diagnosed from RH and cloud water content** (R95)			110%
HONG	qc/qi, qr/qs (2)				240%
IS	qc/qi (1)	**Predicted** (IS)			150%

qc : cloud water, qi : cloud ice
qr : rain, qs : snow

- Efficiency : (HONG5)340%, (HONG6)510%

Cloud scheme (1) : CNTL

- **No cloud water prediction**
- **Precipitation**
  - Supersaturation is removed instantaneously as a precipitation. Evaporation occurs when precipitation falls through the unsaturated atmospheric layer.
- **Stratiform cloud amount**
  - diagnosed from RH (Slingo and Slingo, 1991)

$$\boxed{C = \left(\frac{RH - RH_c}{1 - RH_c} \right)^2}$$

- **Used by ECPC SFM**

Cloud scheme (2) : ZC

- **Predict cloud water/ice mixing ratio**
  (Zhao and Carr 1997)

$$\boxed{\partial q_c/\partial t = A(q_c) + S_c + S_g - P - E_c + D_{qc}}$$

$A(q_c)$: horizontal advection of q_c

$S_{c,}\ S_g$: sources of q_c from convection and grid-scale condensation

P : precipitation production rate from cloud water/ice mixing ratio, evaporation of precipitation, melting snow process

E_c : cloud evaporation rate D_{qc} : horizontal and vertical diffusion

- **Precipitation production**
  - Cloud water -> rain : Sundqvist et al. (1989)

$$\boxed{P_{raut} = c_0\, q_c\{1\text{-}\exp[-(q_c/(q_{cr}b))^2]\}}$$

  - Cloud ice -> snow : Lin et al. (1983)

$$\boxed{P_{saut} = a_1\,(q_c - q_{ci0})}$$

Difference between ECPC and NCEP ZC scheme

- **Cloud water/ice predictive equation**
  - Critical value of autoconversion from cloud ice to snow (kg/kg)

$$\boxed{P_{saut} = a_1\,(q_c - q_{ci0})}$$

NCEP : q_{ci0} = 1.0e-5x (0.01xP)   P(cbar)

ECPC : q_{ci0} = 5.0e-6

→ values in NCEP and ECPC are the same at 500 hPa

- **Cloud amount**
  - Based on Xu and Randall (1996) for NCEP

NCEP

$$C = \max\left[R^{0.25}\left(1-\exp\left\{-\frac{2000\times(q_c - q_{c\min})}{\min[\max([(1-R)q^*]^{0.25}, 0.0001), 1.0]}\right\}\right), 0.0\right]$$

ECPC

$$C = RH\left[1-\exp\left(\frac{-\alpha\cdot m}{1-RH}\right)\right]$$

Cloud scheme (3) : IS

- **Predict cloud water/ice mixing ratio**

  (Tiedtke 1993; Iacobellis and Somerville 2000)

$$\boxed{\partial q_c/\partial t = A(q_c) + S_c + S_{BL} + S_g - P - E_c - ENT + D_{qc}}$$

S_{BL} : sources of q_c from boundary-layer turbulence

ENT : flux divergence due to entrainment processes at the top of stratocumulus clouds

- **Precipitation production**
  - Cloud water / ice -> rain / snow (Sundqvist et al. 1989)

$$\boxed{P_{raut} = c_0\, q_c\{1-\exp[-(q_c/(q_{cr}b))^2]\}}$$

- **Predict cloud amount**

$$\boxed{\partial C/\partial t = A(C) + S(C)_c + S(C)_{BL} + S(C)_g - D(C)}$$

- Used in Scripps SCM, and ECMWF

Cloud scheme (4) : HONG

- **Predict cloud water/ice mixing ratio and rain/snow mixing ratio** (Dudhia 1989, Hong et al. 1998, 2004)

$$\boxed{\begin{aligned}\partial q_c/\partial t &= A(q_c) + F(q_c) + D_{qc}\\ \partial q_r/\partial t &= A(q_r) + F(q_r) + D_{qr} - P\end{aligned}}$$

$A(q_c)$, $A(q_r)$: horizontal and vertical advection of q_c and q_c

$F(q_c)$, $F(q_r)$: microphysical processes

P : precipitation production rate, D : horizontal and vertical diffusion

  - The microphysical processes in the scheme contain condensation of water vapor into cloud water (ice) at saturation, accretion of cloud by rain (ice by snow), evaporation (sublimation) of rain (snow), initiation of ice crystals, and sublimation or deposition of ice crystals

- **Precipitation**
  - Cloud water -> rain : Kessler (1969)

$$\boxed{P_{raut} = a\,\rho(q_c - q_{c0})}$$

  - Cloud ice -> snow :

$$\boxed{P_{saut} = \rho(q_i - q_{imax})/\,\Delta t}$$

Cloud scheme (4) : HONG

- **Stratiform cloud amount**
  - diagnosed from RH and cloud water/ice mixing ratio (Xu and Randall 1996) same as **ZC**

$$C = RH\left[1-\exp\left(\frac{-\alpha\cdot m}{1-RH}\right)\right]$$

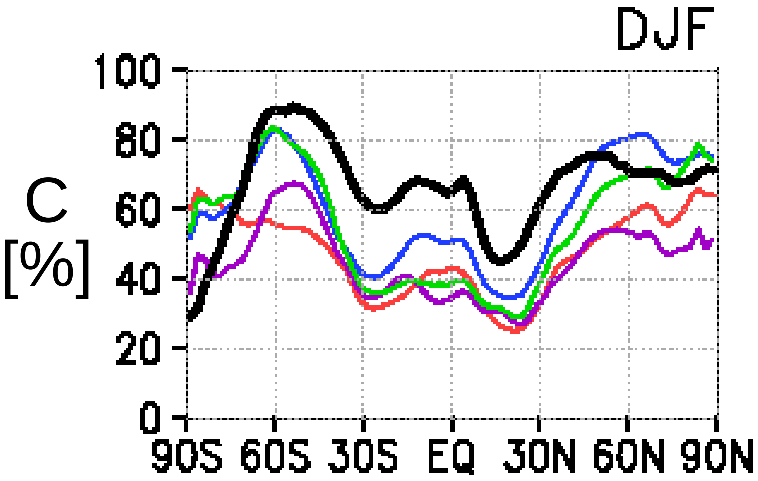
α : $1.0\text{x}10^3$ (same as in R95)

- Used by NCEP WRF/RSM

Experimental design

- ECPC G-RSM : Based on the NCEP Seasonal Forecast Model (SFM; Kanamitsu et al. 2002)
- GSM T62L28
- Initial time : 01/Jan/1989, 00Z
- Integration : 11 years (1989-1999), first year removed for validation.
- 1 member
- SST : interpolated daily from NCEP weekly analysis (Reynolds and Smith 1994)

Total cloud amount



- Underestimated in all schemes. **CNTL** is the smallest. **IS** is closer to OBS than others.
- **IS**>**HONG**>**CNTL**,**ZC**

DJF

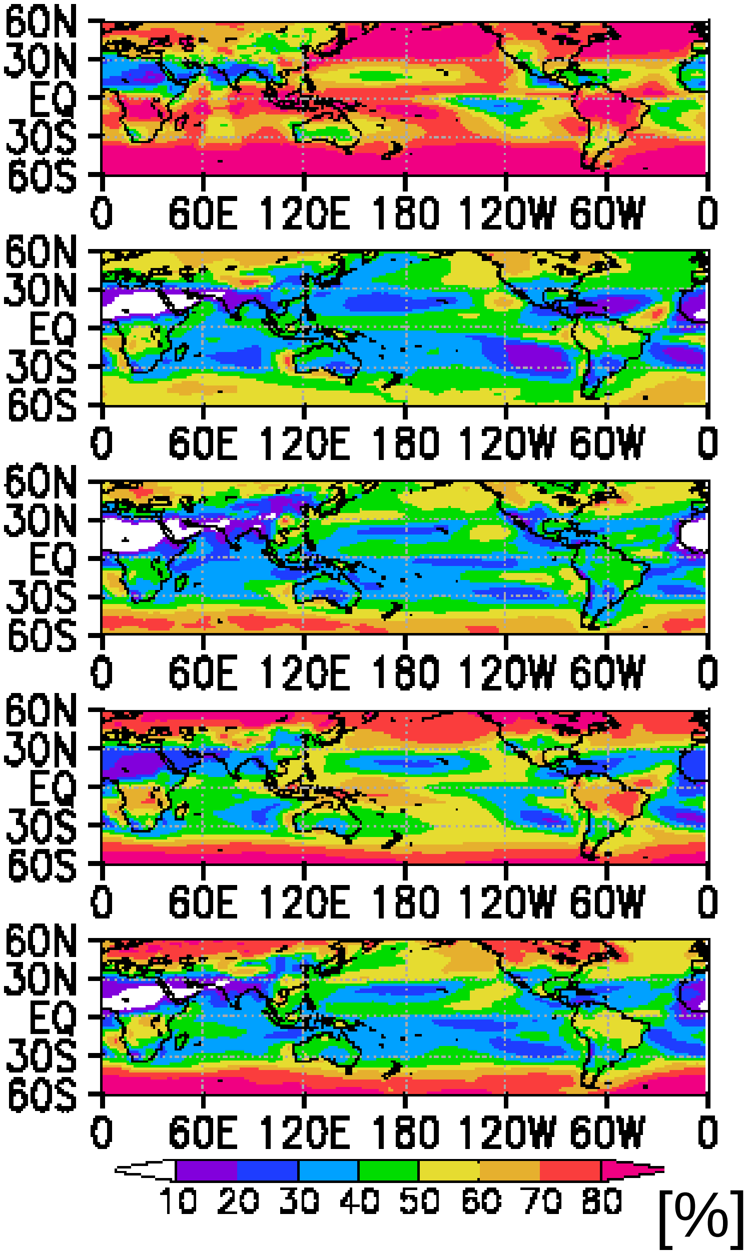
ISCCP (OBS)

CNTL

ZC

IS

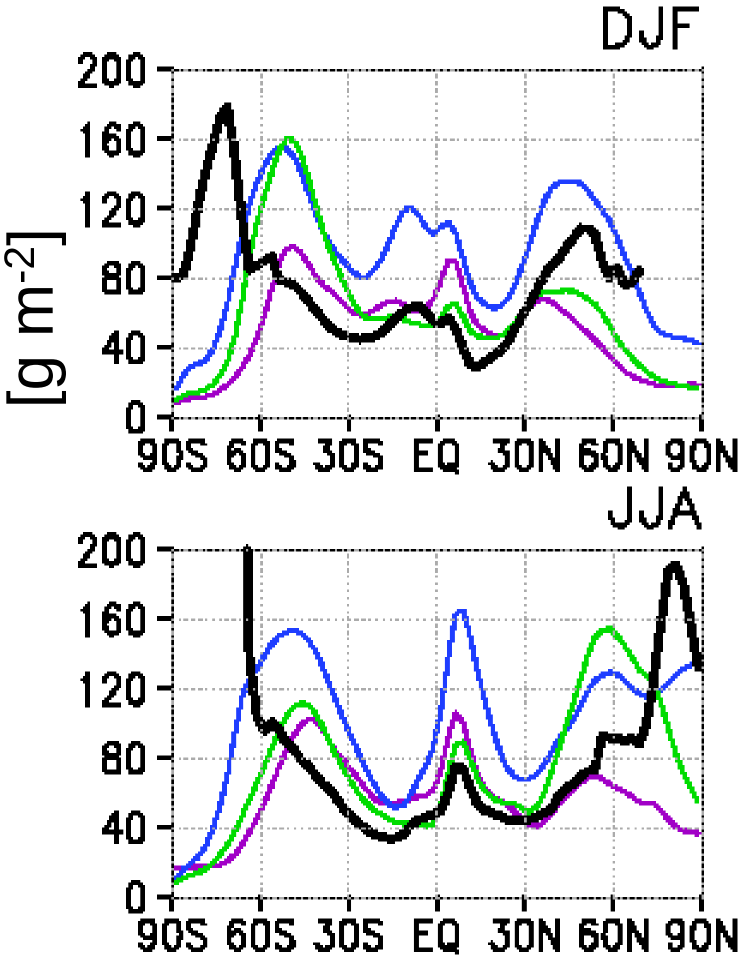
HONG



Summary of cloud amount comparison

- High cloud:
  - **IS**>**CNTL**,**HONG**>**ZC**. **CNTL** and **HONG** are better. **IS** overestimates, **ZC** underestimates. Overestimation in **IS** is caused by neglecting falling cloud ice. Underestimation in **ZC** is caused by small value of autoconversion from cloud ice to snow.
  - Anvil in **ZC**, **IS** and **HONG** seems to be underestimated.
- Middle cloud
  - **IS**>**CNTL**,**HONG**>**ZC**. **CNTL** and **HONG** are better. **IS** is overestimated, **ZC** is underestimated. All similar to high cloud.
- Low cloud
  - **HONG**, **IS**>**ZC**>**CNTL**. Using cloud water show larger cloud amount.
  - **ZC** is better in tropics over ocean.
- Total cloud
  - Underestimated in all. **IS** is closer to observation.

Cloud water path



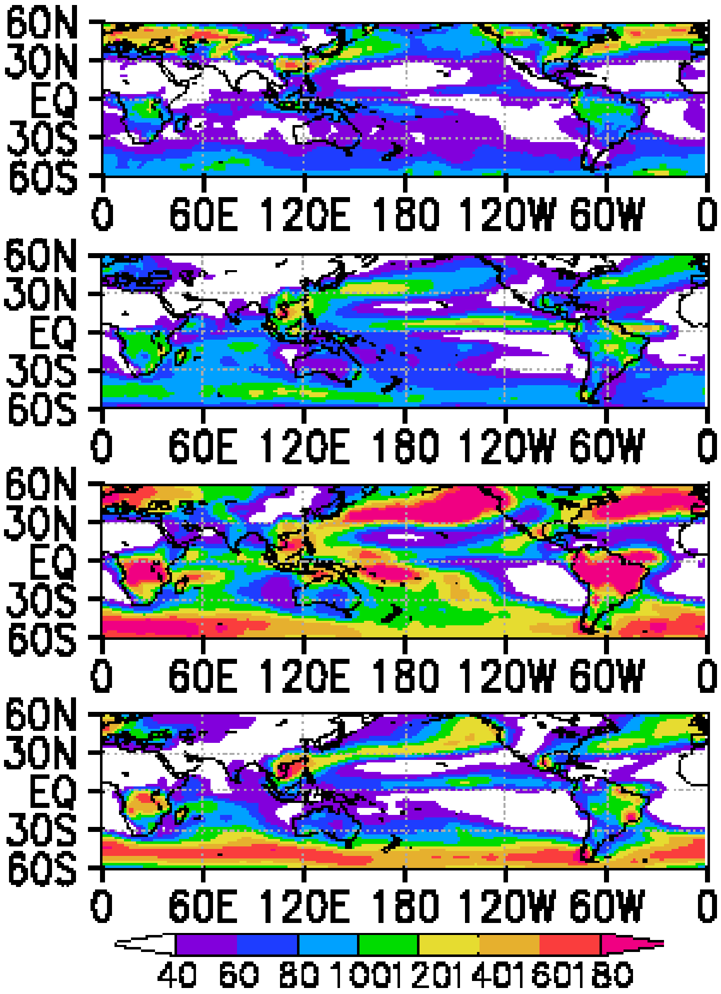
DJF

ISCCP (OBS)

ZC

IS

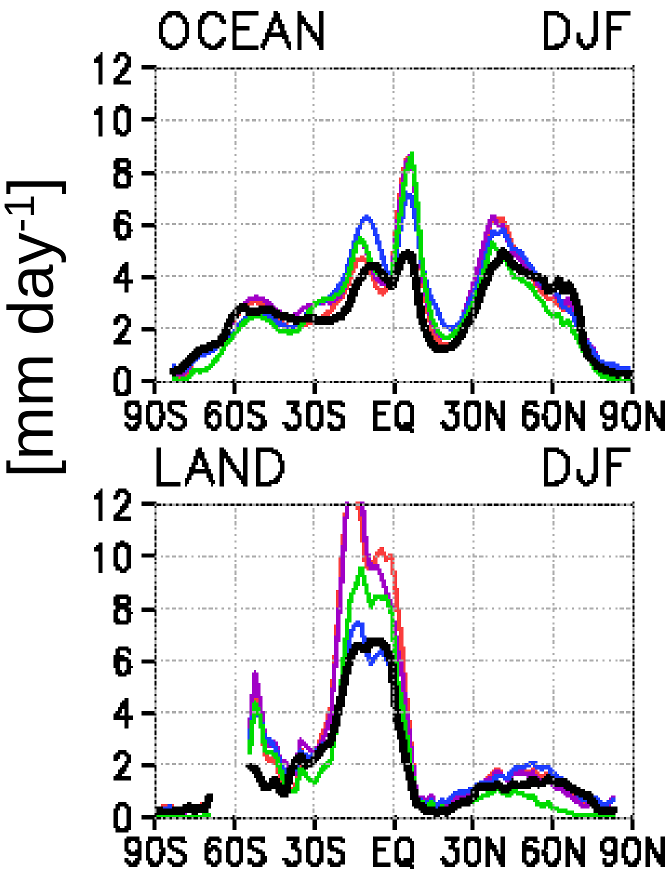
HONG

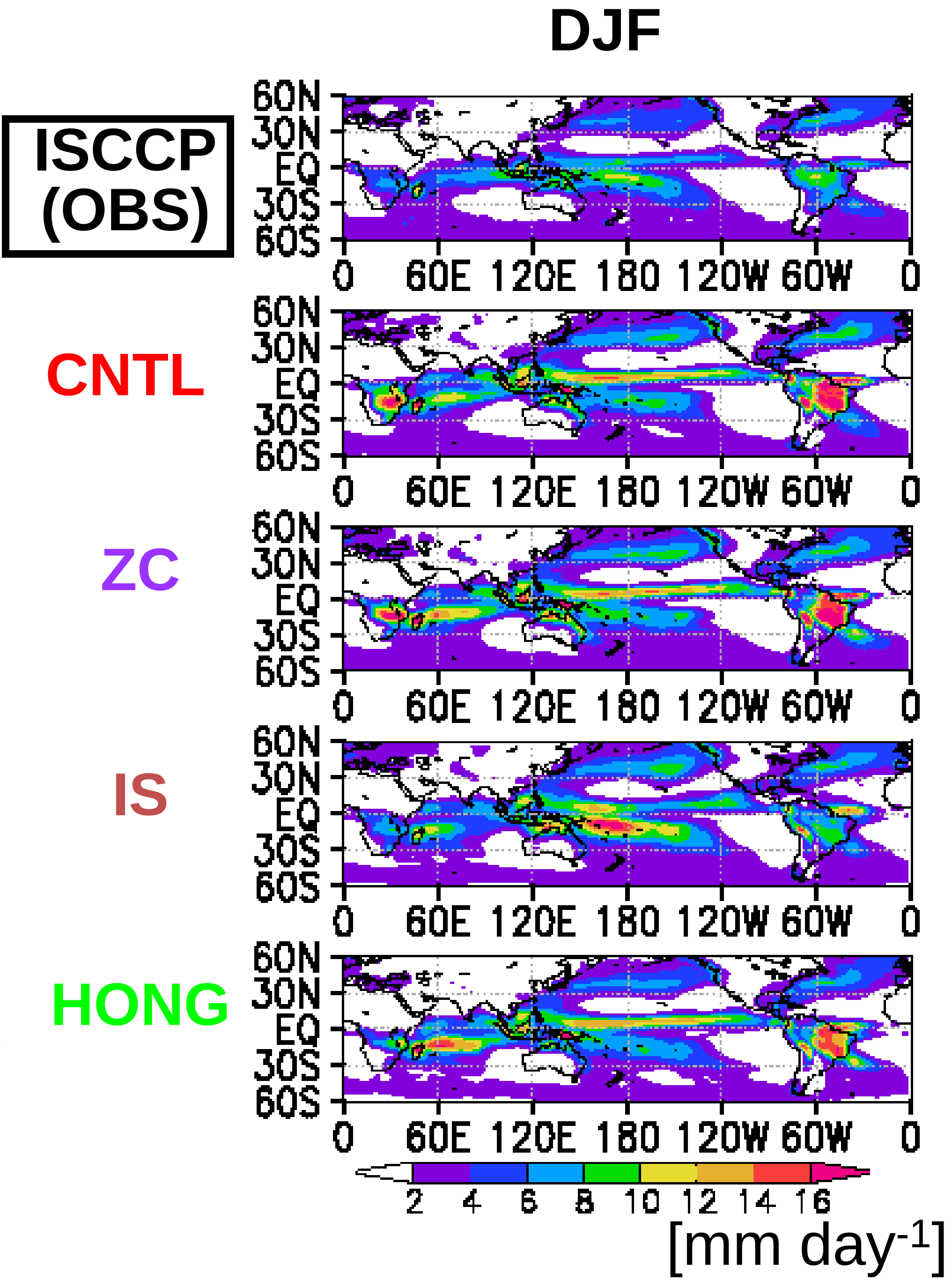


[g m^{-2}]

- **ZC** : closest to observation. Underestimated over land in NH in DJF
- **IS**: overestimated ,except for over land in NH mid latitude in DJF
- **HONG**: seasonal change is large. Sum>Win. Over estimation in summer hemisphere. Underestimated over land in NH in DJF like **ZC**.

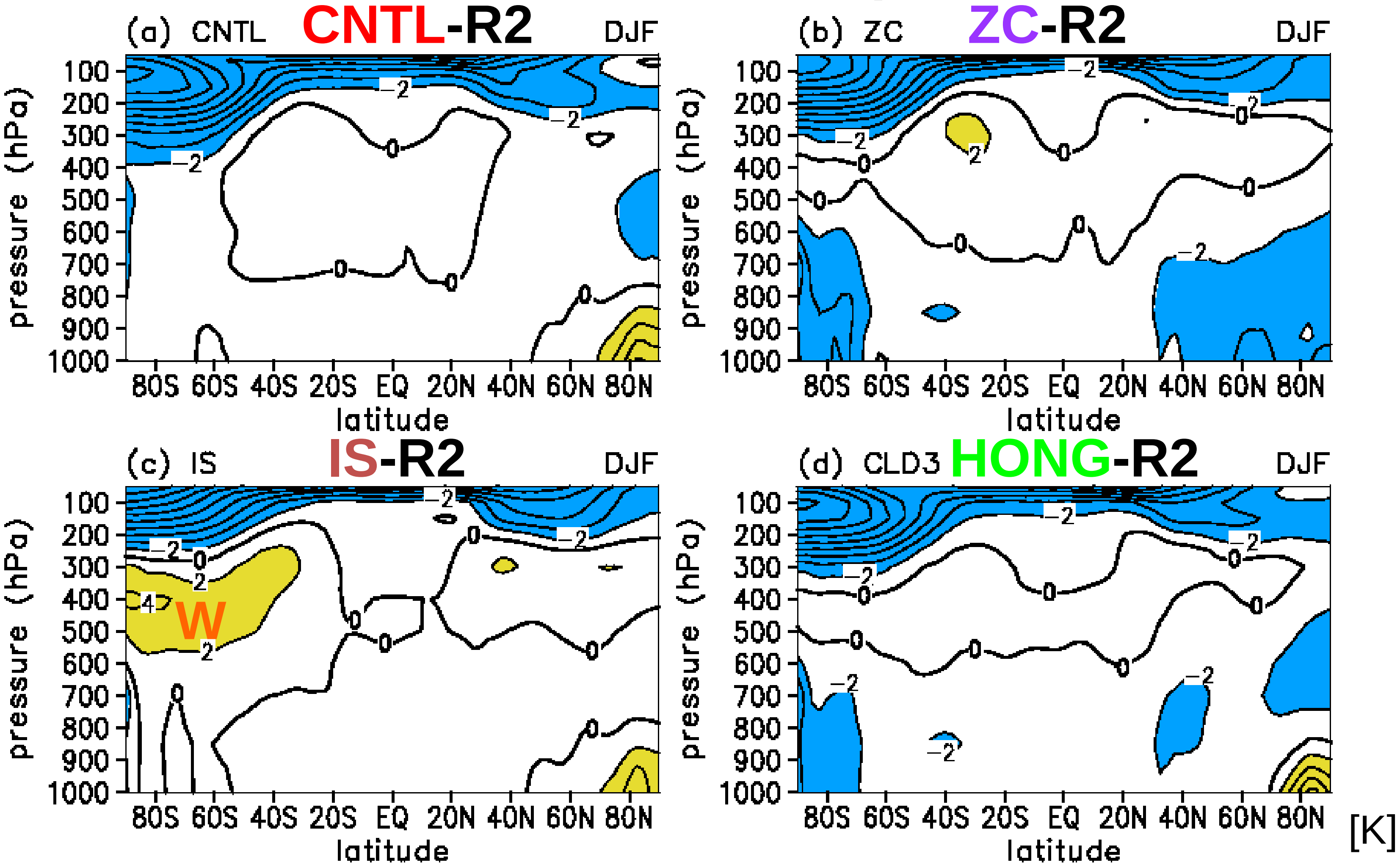
Precipitation





- Double ITCZ problem is seen in all schemes. Overestimation in TROPICS and winter hemisphere.
- TROPICS: **CNTL**, **ZC** and **HONG** show similar precipitation distribution. **IS** seems to be good over land. Over ocean, contrast between ITCZ and SPCZ is better than others.over land, also **IS** is good.
- **HONG** shows underestimation, especially over land.
- JJA is similar to DJF

Zonal mean Temperature



CNTL-R2

ZC-R2

IS-R2

HONG-R2

- Cold bias is common to all schemes in stratosphere.
- Warm bias is seen around troposphere, especially **IS** and **ZC**. This is related with the radiative properties calculated from cloud water content. In **IS**, it is warmer in summer hemisphere. It is interesting that warm bias is not strong in **HONG**, in which cloud water path is between **ZC** and **IS**.
- **CNTL** seems to be the best in 4 schemes.
- JJA pattern reverse between NH and SH.

Summary of comparisons

- **Cloud water path**:
  - **IS**>**HONG**>**ZC**. **ZC** is the closest to observation.
  - Seasonal change seen in **HONG** is large. Summer > Winter.
- **Precipitation**
  - Overestimated in all schemes. Tendency to form double ITCZ in all.
  - Over land, **IS** shows closer precipitation distribution to observation.
  - **HONG** shows underestimation over land in mid latitudes.
- **Temperature**
  - **CNTL** has smallest bias.
  - Warm bias is seen around tropopause in **IS**. This seems to be related with a lot of cloud water in high latitudes.
- **Radiation fluxes at TOA**
  - OLR: Over ocean, overestimated most in **ZC**. Related with least high cloud amount. **IS** is closest to observation, however high cloud amount is overestimated. Over land between 30S-EQ, **CNTL** high cloud amount is the best of all. Insufficient representation of anvil in other schemes.
  - OSR: **IS** or **HONG** is the best. Total cloud amount which matches best with observation, is responsible.

Remarks

- Radiation is directly interacted by cloudiness which is most intimately interacted with precipitation physics. In other words, cloudiness associated with cloud-radiation interaction is affected by the precipitation physics as well as cloudiness parameterization.
- It has been found that implementation of the prognostic cloud scheme necessitates the improvement of the radiative transfer of both longwave and shortwave in the atmosphere.

For the use of WSM3, which is more realistic scheme than WSM1, new formula for cloud amount calculation is needed to have realistic representation of cloud-radiation interaction.

In other words, it is difficult to remove empirical tuning parameters in the diagnostic cloudiness formula

Re-examination of cloudiness parameterization

- Cloudiness is important for:
  - Model simulations using 4 cloud schemes showed TOA is sensitive to simulated cloud distributions.
  - Simulated cloud distribution closer to observation results in better radiation fluxes at TOA.

Re-examination of the cloudiness parameterization

- Examine relationships between relative humidity and cloudiness, and cloud water and cloudiness in observation

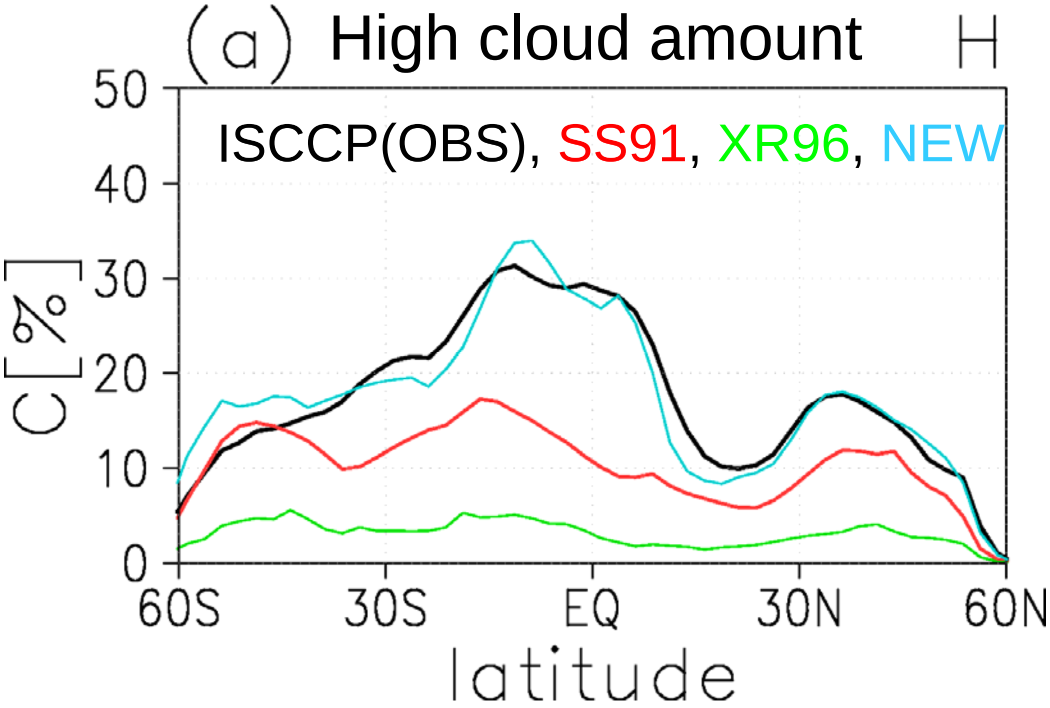
- Observation used
  - ISCCP(D2): cloud amount, cloud water path
    - 3 levels : high/middle/low
  - NCEP/DOE reanalysis 2 (R2) : relative humidity
    - Maximum in each level

A proposed formulation of cloud amount using cloud water

$$\boxed{C = 1-\exp(-\beta \cdot q_c)}$$

- *ß* (constant)

← ISCCP D1 (6 hourly)



- This formulation is similar to Randall (1995)'s formulation, but does not include the term associated with RH. To determine the constant ß, ISCCP D1 data (6-hourly) is used.
- The accuracy of predicted cloud water distribution in the model becomes very important since cloud water is an only predictor in the proposed parameterization. Bias in cloud water may harm this scheme.

Microphysics versus cloudiness in WRF : short-range vs. long-range

Experiments

MPS	Cloud fraction (0 or 1)
MPS_CLD	Cloud fraction based on Xu and Randall 1996

MPS: WSM6/ WDM6/ PLIN

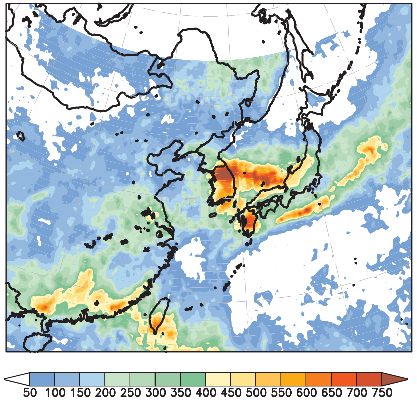
-Case:

1)climate run: Jang-ma season →**2006.7-8 (1 month)**

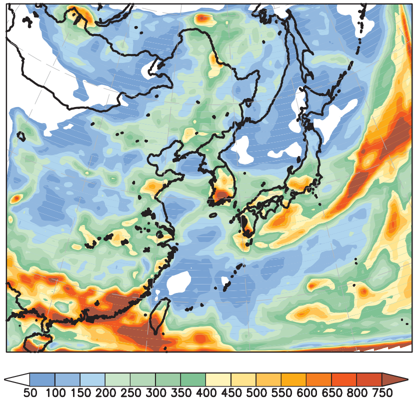
2)Short range forecast run: Heavy rain fall→ **2006.7.15-16 (1day)**

Accumulated rainfall 2006.7-8 (1 month)

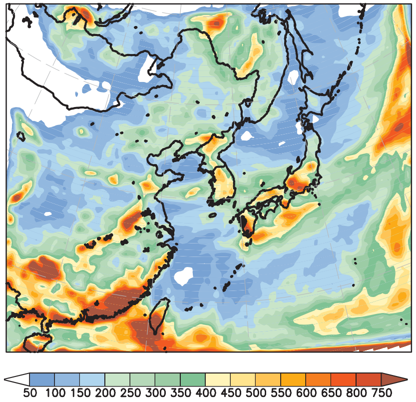
TMPA



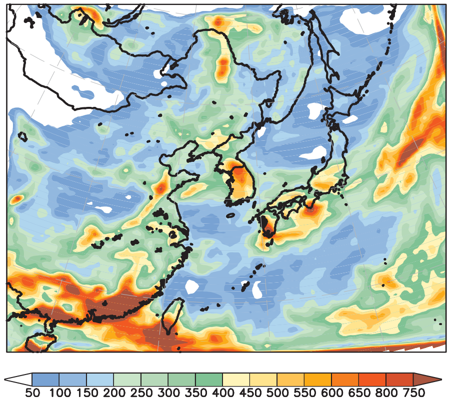
WSM6



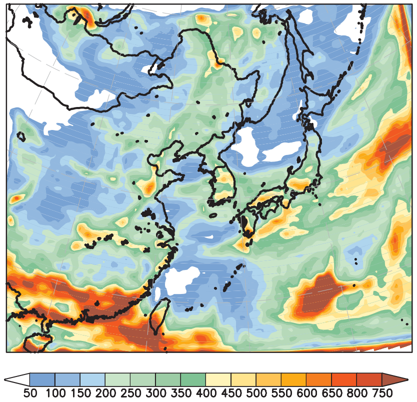
WDM6



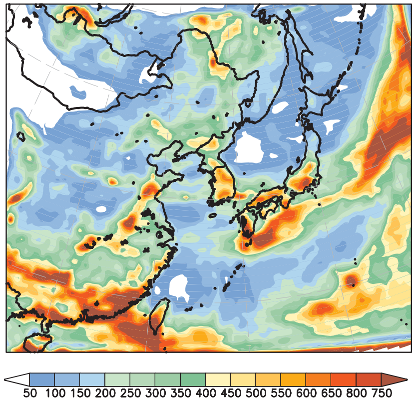
PLIN



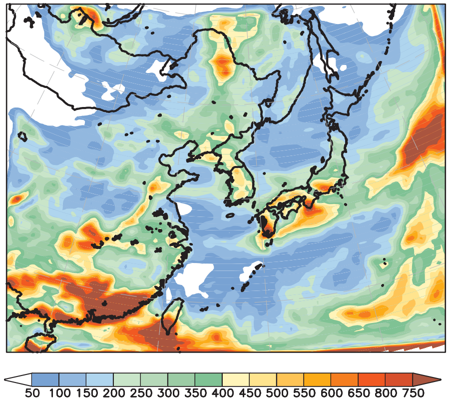
WSM6_CLD



WDM6_CLD



PLIN_CLD

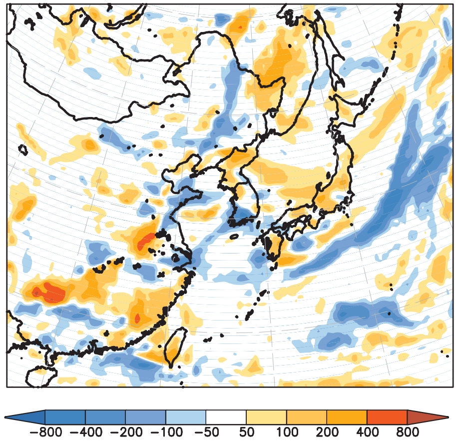


Standard Deviation

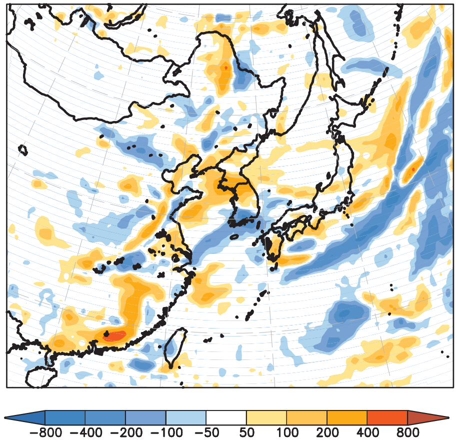
MPS	**63.54**
CLOUD FRACTION	**62.09** (WSM6: 74.14,WDM6: 59.77,PLIN: 52.35)

Differences in accumulated rainfall 2006.7-8 (1 month)

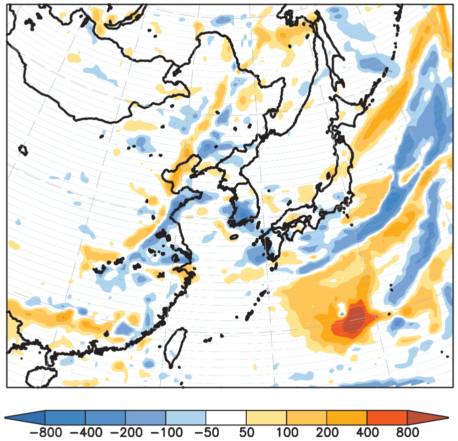
WDM6-WSM6



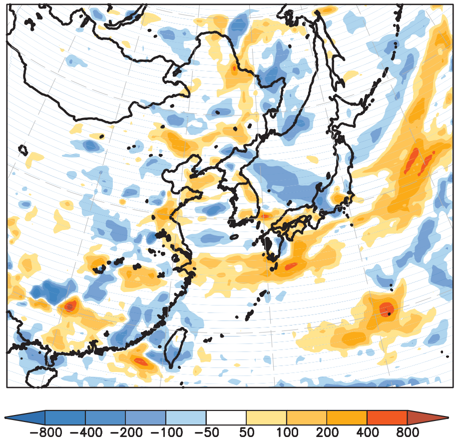
PLIN-WSM6



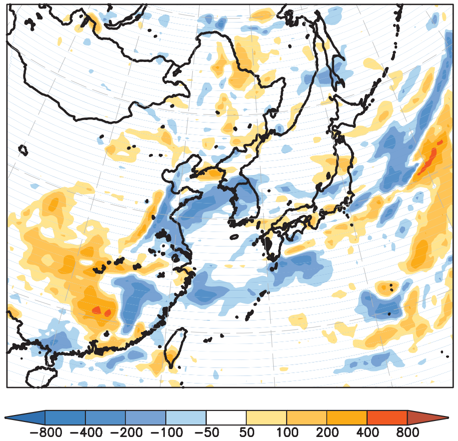
WSM6_CLD-WSM6



WDM6_CLD-WDM6



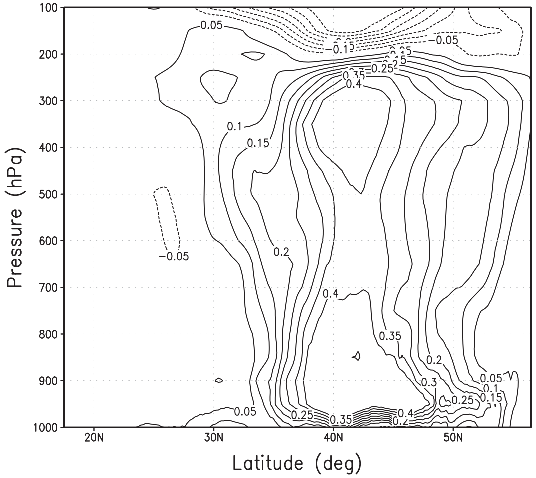
PLIN_CLD-PLIN



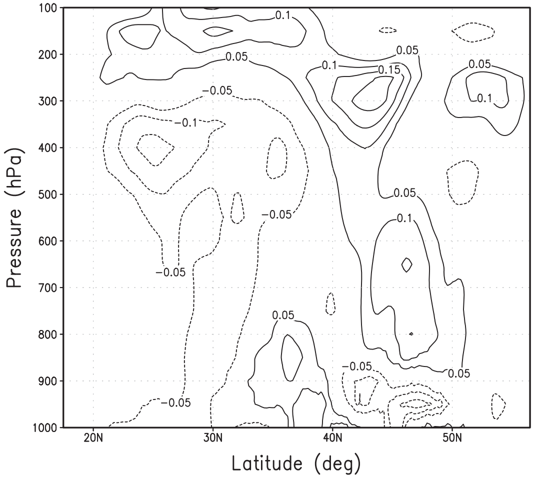
Differences in temperature

2006.7-8 (1 month)

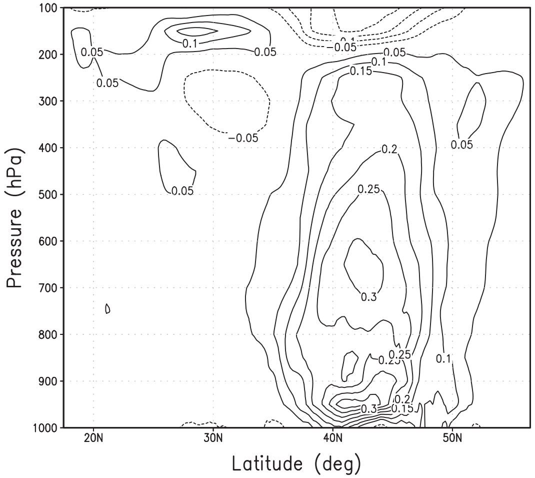
WDM6-WSM6



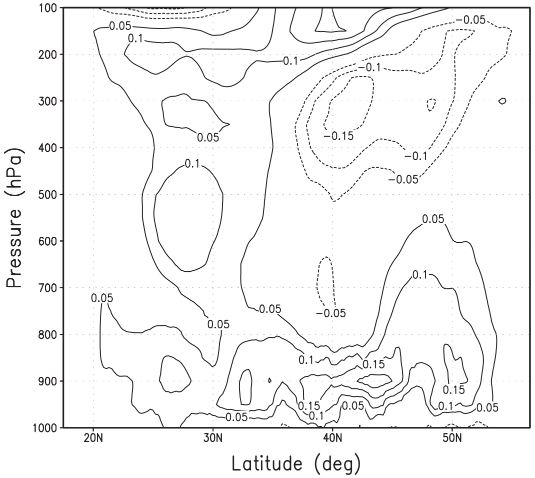
PLIN-WSM6



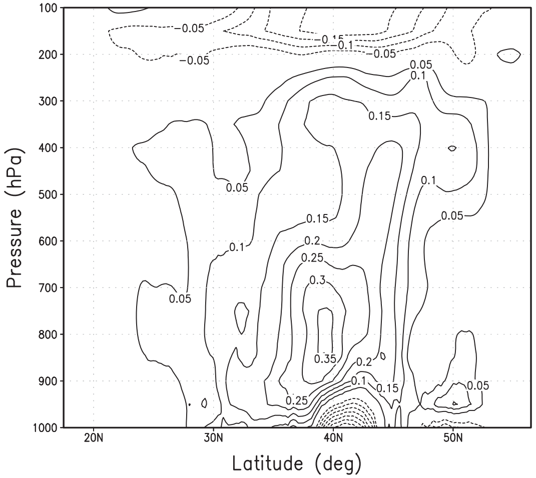
WSM6_CLD-WSM6



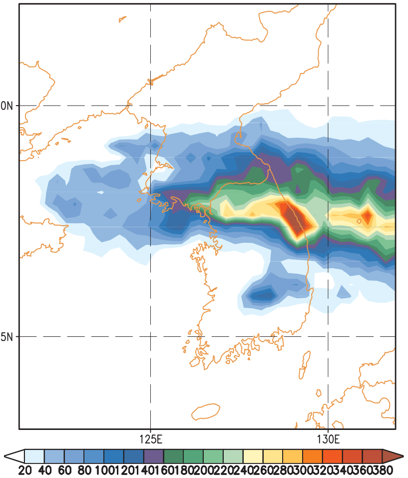
WDM6_CLD-WDM6



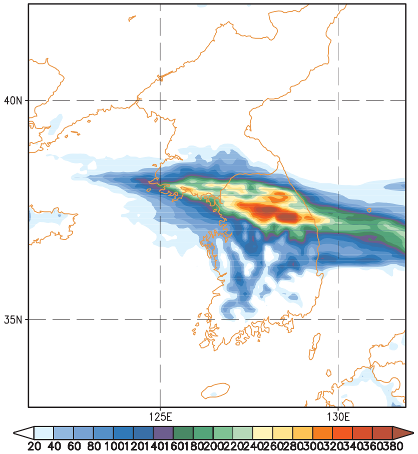
PLIN_CLD-PLIN



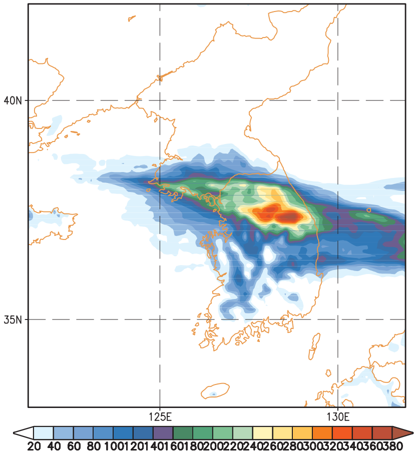
Accumulated rainfall 2006.7.15-16 (1day)



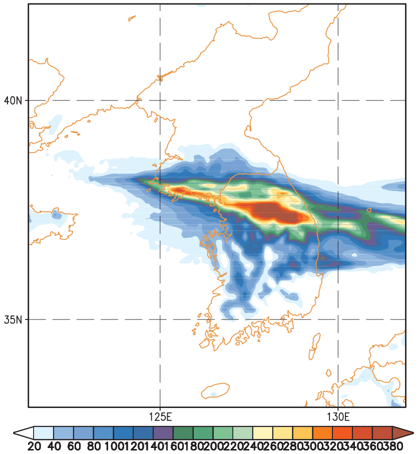
TMPA



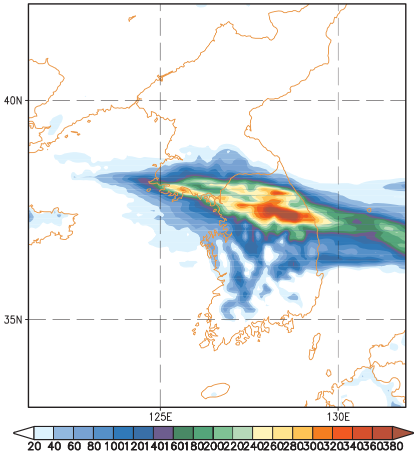
WSM6



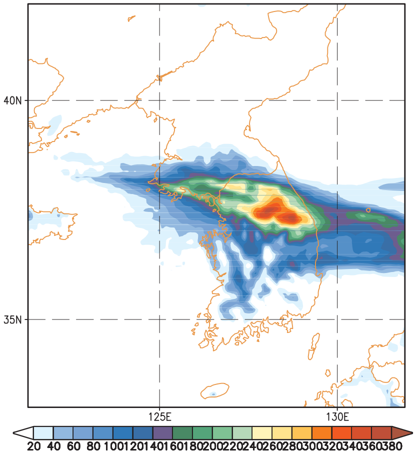
WDM6



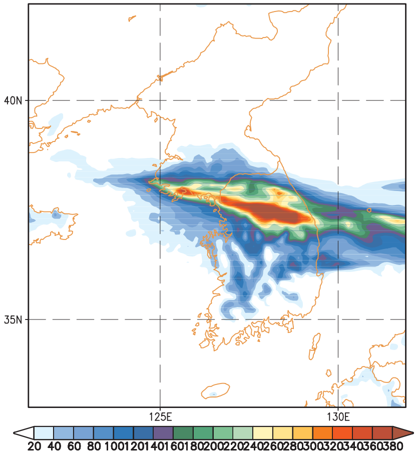
PLIN



WSM6_CLD



WDM6_CLD



PLIN_CLD

Standard Deviation

MPS	**8.28**
CLOUD FRACTION	**3.45** (WSM6: 3.77,WDM6: 3.08,PLIN: 3.50)

Microphysics is important in Short-range forecast, whereas formula for cloudiness becomes important with time

Cloudiness effect in a simulated climatology

Experiments

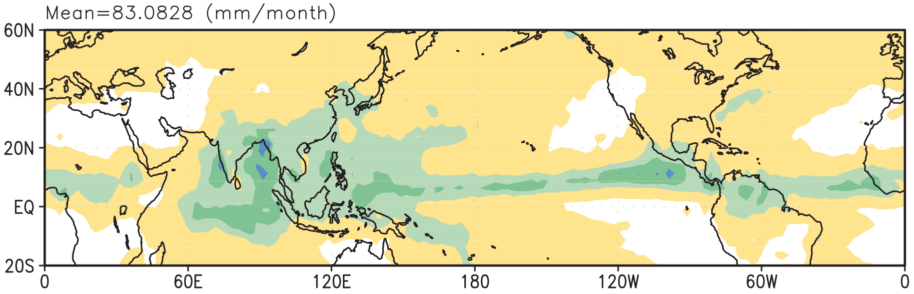
GSFC_GRIMs	GSFC radiation in GRIMs (routed in GFDL scheme back to early1990)
GSFC_WRF	GSFC in the WRF, which was implemented into the GRIMs
GSFC_WRF_CLD	Changing the cloud fraction from the WRF (0,1) to GRIMs (partial)

-Case:

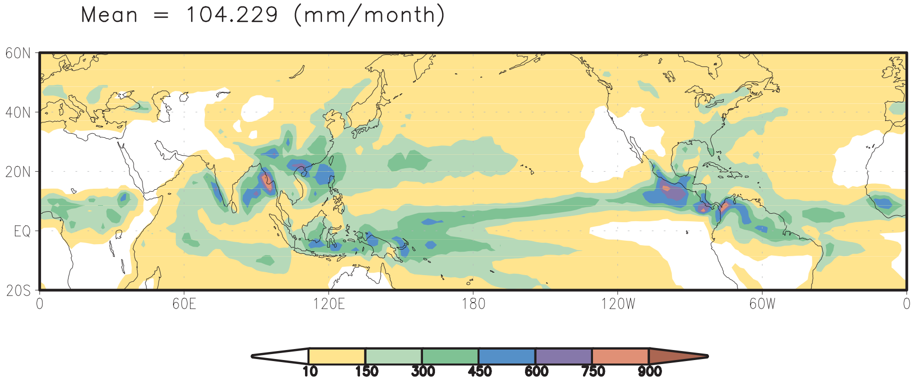
climate run: summer season →**1997.6-8 (3 month, spin-up:1 month)**

Accumulated rainfall : GRIMs T62 1997.6-8 (3 month)

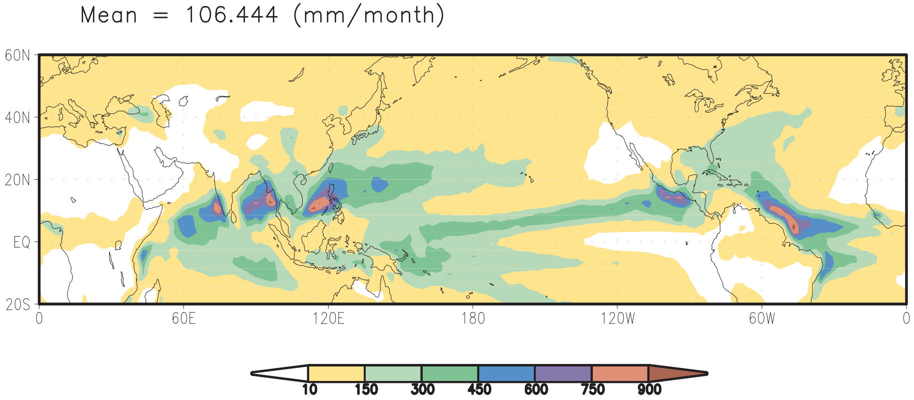
CMAP


Mean=83.0828 (mm/month)

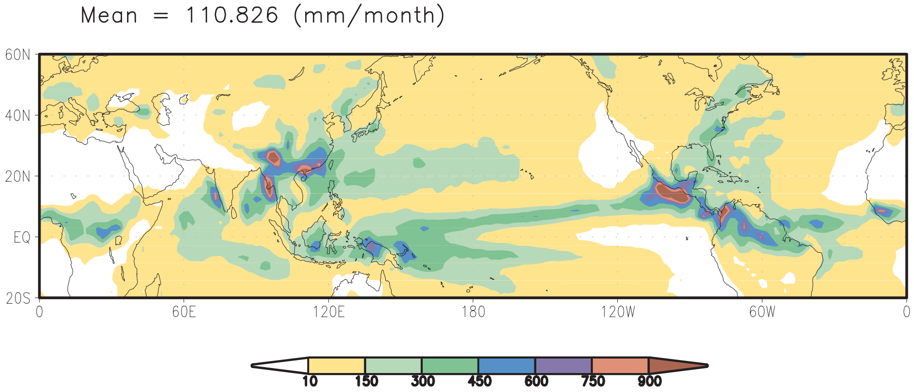
GSFC_GRIMs


Mean = 104.229 (mm/month)

GSFC_WRF


Mean = 106.444 (mm/month)

GSFC_WRF_CLD


Mean = 110.826 (mm/month)

Statistics

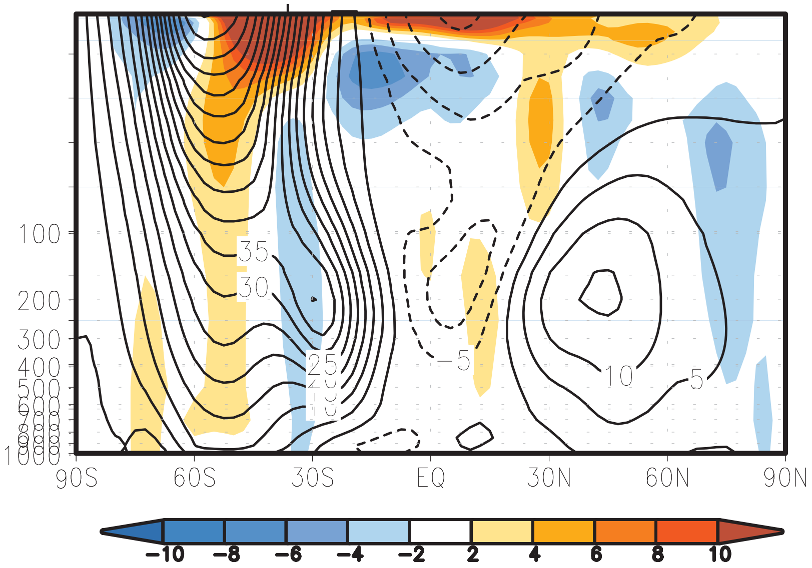
	Global Mean	Pattern Correlation
GSFC_GRIM	104.2	0.73
GSFC_WRF	106.4	0.64
GSFC_WRF_CLD	110.8	0.67

Zonal Mean U winds

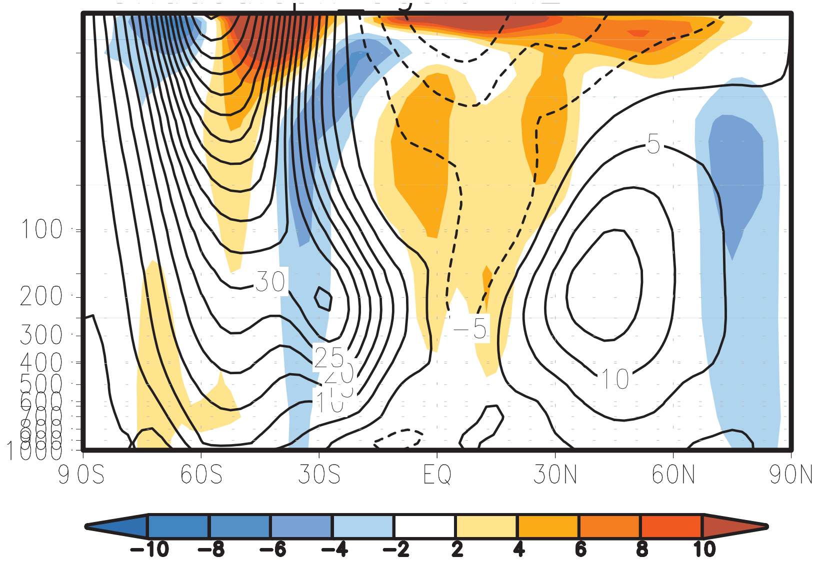
contour: zonal mean U wind

shaded: exp – RA2

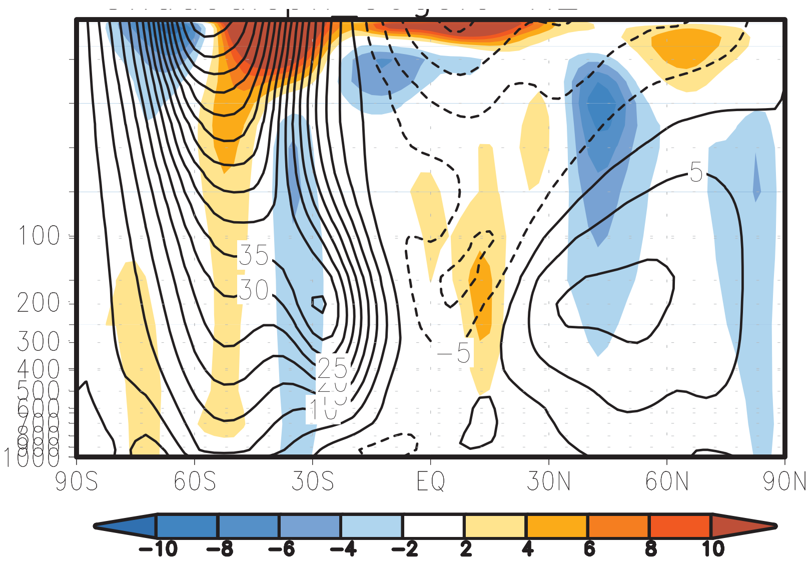
GSFC_GRIMs



GSFC_WRF



GSFC_WRF_CLD

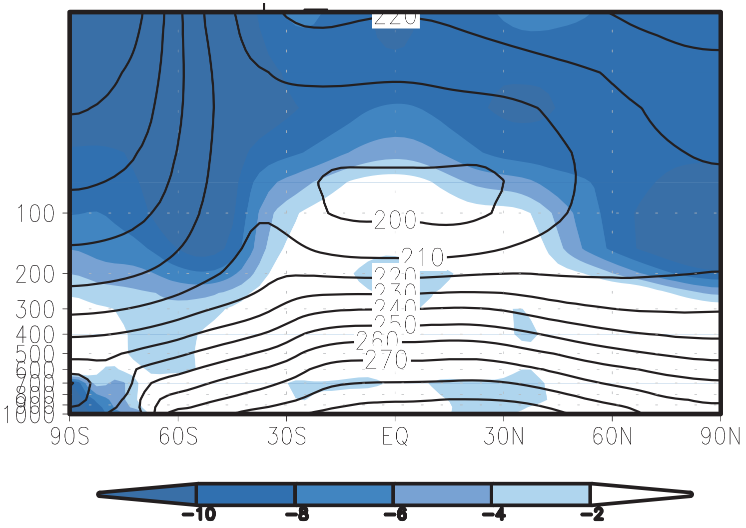


Zonal Mean Temperature

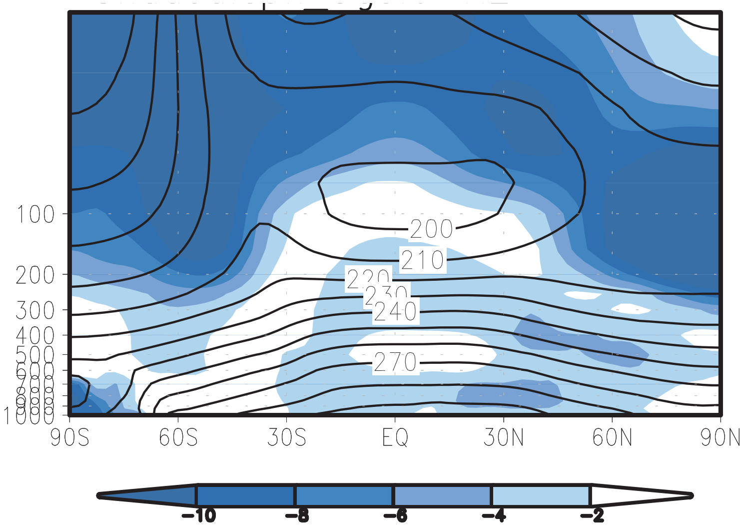
contour: zonal mean Temperature

shaded: exp – RA2

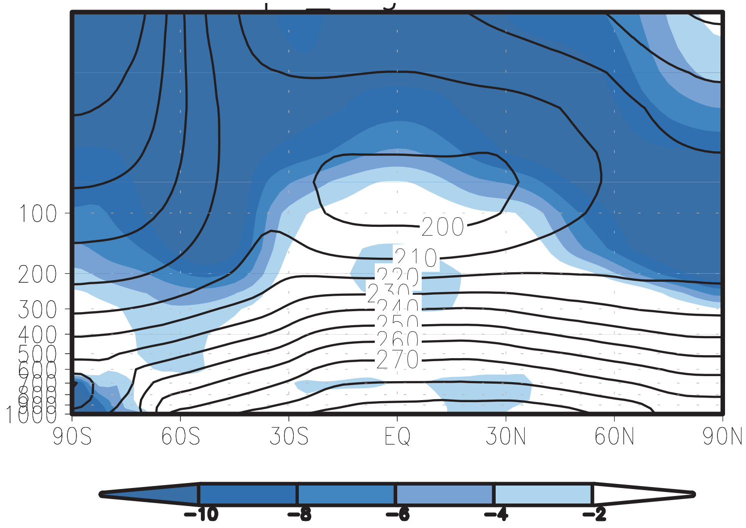
GSFC_GRIMs



GSFC_WRF



GSFC_WRF_CLD



Remarks on cloudiness

RH, T, are synoptic observed variables
Hydrometeors can be observed recently
Cloudiness is difficult to measure
Overlapping is also uncertain

Cloudiness is a muddy physics component, but becomes important for a longer integration, even at higher resolutions

Thanks~*